Evaluating the impact of variable en route mortality on spatially varying harvest strategies for Fraser River sockeye (*Oncorhynchus nerka*)

by

Angus Hunter Straight

BA, Carleton University, 2012

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management

in the
School of Resource and Environmental Management
Faculty of Environment

Report No. 762

SIMON FRASER UNIVERSITY
Spring 2021

Declaration of Committee

Name:	**Angus Hunter Straight**
Degree:	**Master of Resource Management**
Title:	**Evaluating the impact of variable en route mortality on spatially varying harvest strategies for Fraser River sockeye (*Oncorhynchus nerka*)**
Committee:	**Chair: Daniella LoScerbo** Master of Resource Management Candidate **Sean P. Cox** Supervisor Professor, School of Resource and Environmental Management **David A. Patterson** Committee Member Adjunct Professor, School of Resource and Environmental Management

Abstract

Single stock terminal fisheries for Fraser River sockeye salmon (*Oncorhynchus nerka*) have been proposed as an alternative to lower-river mixed-stock fisheries to avoid weak stocks and support terminal allocation objectives. However, increasing natural mortality rates during the upriver migration (en route mortality) have been overlooked when evaluating alternative harvest strategies. I used a spatially explicit, individual based model of sockeye migration and fisheries to examine how fishery location options affect management performance under variable en route mortality scenarios and a fixed total catch objective. Under all scenarios tested, re-distributing a fixed total harvest from lower-river mixed-stock to multiple upper-river single stock terminal fisheries resulted in increased en route mortality, decreased spawner abundance, and, in most cases, reduced total catch. While lower-river mixed-stock fisheries performed better at meeting a fixed catch objective under the scenarios in my analysis, single stock terminal fisheries may be preferable for meeting other objectives.

Keywords: Fraser River; sockeye salmon; en route mortality; terminal fisheries; mixed-stock fisheries; harvest strategies

Acknowledgements

I would like to thank my supervisors Sean Cox and David Patterson for their support throughout this project, and for all the knowledge they shared. To the DFO team, especially Kendra Robinson and Daniella LoScerbo, thank you for all the help with data, brainstorming, and moral support. To all the past and current Quantitative Fisheries Research Group students, especially Midoli Bresch, Jessica Gill, and Sam Johnston, your coding help and conversations have been invaluable. Lastly thank you to my family for their unwavering support and encouragement throughout my studies.

Table of Contents

List of Tables

List of Figures

1. Introduction

Recent declines in Pacific salmon returns to the Fraser River have resulted in increased scrutiny of mixed-stock harvest practices (DFO, 2018b). Mixed-stock harvest historically simplified management and allowed for efficient harvest of aggregated salmon stocks in marine approach and lower-river fisheries. More recently, there has been a push from First Nations, academics, and conservation groups for more upstream or terminal harvest of single stocks to protect stocks with lower productivity and allow for greater location flexibility for harvesters (Atlas et al., 2020; Kemp, 2018). However, previous evaluations of mixed-stock fishery alternatives have not quantified the impact of freshwater migration mortality, most commonly associated with increasing river temperatures, on harvest and escapement goals(Hanson et al., 2008; Holt & Peterman, 2006)

Management of most salmon fisheries begin with the establishment of spawner escapement goals, the number of successful spawners required for replacement (minimum goal) and additional spawners for maximum sustainable yield (maximum goal) (Mace & Sissenwine, 1993). Surplus returns over and above escapement goals are typically harvested in mixed-stock fisheries managed in spatial aggregates (Stephenson, 2002). The heterogenous stocks comprising a mixed-stock fishery can differ in spawning location, timing, productivity and conservation status (Hilborn, 1985; Ricker, 1973). Migrating salmon must “run the gauntlet” through marine and lower-river fisheries before continuing their upstream migration. Gauntlet style mixed-stock salmon fisheries (eg., Bristol Bay , Fraser River) front-load harvesting to early parts of the migration (lower-river areas), at the expense of higher risks for meeting stock-specific escapement goals (Wright, 1981). The front-load harvest of mixed-stock salmon fisheries is to (1) allow for harvest of high-density aggregations of fish, (2) simplify management and, (3) catch high commercial value fish (i.e. price per kg) (Freshwater, Holt, Huang, & Holt, 2020; Hilborn, 1985; Routledge, 2001). Meeting escapement goals can be complicated in mixed-stock fisheries because it is difficult to account for uncertainty and fluctuations in the composition of the co-migrating stocks, number of fish migrating (run size), arrival timing to the river, and natural mortality which can all impact stock specific escapements (Freshwater et al., 2020; Holt & Peterman, 2006; Walters, 1975).

Mixed-stock salmon fisheries in the marine approach or lower river have the capacity to over-/under-harvest leading to foregone catch and/or conservation concerns (Freshwater et al., 2020; Hilborn, 1985; Holt & Peterman, 2006; Ricker, 1973). Mixed-stocks, with differing levels of productivity and susceptibility to spatially and temporally varying natural mortality, pose a challenge for the management of many commercial fisheries as some stocks may be more vulnerable to recruitment overfishing when harvest levels are based on the average productivity and natural mortality of mixed-stocks (Forrest, Holt, & Kronlund, 2018; Jónsdóttir, Marteinsdottir, & Campana, 2007; Morse, Kerr, Galuardi, & Cadrin, 2020). Overfishing less productive stocks in mixed-stock fisheries can reduce overall resiliency of the collective population (Hilborn, Quinn, Schindler, & Rogers, 2003; Satterthwaite & Carlson, 2015; Schindler et al., 2010). Conversely, underfishing of stocks with high productivity and lower en route mortality has the potential to reduce the yield of the next generation and may result in short- and long-term economic losses under certain stock-recruitment assumptions (Larkin, 1971; Ricker, 1973). Single-stock, terminal fisheries are a proposed alternative to managing mixed-stock fisheries to the weakest stock, while still allowing for harvest opportunities (Freshwater et al., 2020; Gayeski et al., 2018).

Terminal fisheries, herein defined as fisheries targeting a single stock through the use of geographically distinct fishing grounds, provide a tactic for harvest of a single stock (Knudsen, 1999). The use of terminal fisheries as a harvest tactic to reduce pressure on weaker stocks is a key recommendation in Canada's Wild Salmon Policy (DFO, 2018b). Conservation groups have also suggested that terminal fisheries be utilized in order to "[…] rebuild endangered salmon populations, maintain the ecological health of our watersheds, and support economic development in First Nations fishing communities." (Kemp, 2018) Most recently, Atlas et al. (2020) suggest that the rebuilding of Indigenous terminal fisheries could allow for increased conservation and greater harvest opportunities under high levels of uncertainty and depressed population sizes (Atlas et al., 2020). However, it is unclear whether escapement goals and catch opportunities as current defined by management will be better met through the use of terminal fisheries, given the potential impact of rising levels of in river migration mortality.

En route mortality of Pacific salmon, herein defined as mortality that takes place between entering the freshwater environment and spawning grounds, has been reported in multiple river systems and for multiple Pacific salmon species across large latitudinal gradient, including the following: Koyukuk chum, Alaska, US (Westley, 2020), Auke pink salmon, Alaska, US (J. D. M. Ray, Sethi, Eiler, & Joyce, 2015); Fraser sockeye salmon, BC, Canada (Martins et al., 2011), Somass sockeye (Pellett, Stiff, Damborg, & Hyatt, 2015), Cedar sockeye, Washington, US (Barnett, Quinn, Bhuthimethee, & Winton, 2020), Columbia Chinook, Oregon, US (Keefer et al., 2005) , Klamath chinook and coho, California, US (R. A. Ray, Holt, & Bartholomew, 2012), Sacramento and San Joaquin chinook, California, US (Bowerman, Keefer, & Caudill, 2016). Suspected causes of en route mortality include disease (Bradford, Lovy, Patterson, et al., 2010; Jones et al., 2004), water quality (Scholz et al., 2011), water temperature (Hinch et al., 2012), discharge (Macdonald, 2000), fishing related incidental mortality (Patterson et al., 2017), extended freshwater residence (Quinn, McGinnity, & Reed, 2016; J. D. M. Ray et al., 2015), and barriers to migration (Bowerman et al., 2016; Budy, Thiede, Bouwes, Petrosky, & Schaller, 2002; Godfrey, Hourston, Stokes, & Withler, 1954; Keefer et al., 2005) (hydroelectric dams, rockslides, etc.). High river temperature is conspicuous across all wild salmon species, resulting in short- and long-term temperature exposure mortality. Temperature related mortality has been identified as a key contributing factor to en route mortality for chinook (Keefer et al., 2015; McCullough, 1999), sockeye (Farrell et al., 2008; Hinch et al., 2012; Macdonald, Patterson, Hague, & Guthrie, 2010), steelhead (Wade et al., 2013), chum (Westley, 2020) and pink (Fukushima & Smoker, 1997). The impact of water temperature on salmon survival is function of temperature level and the duration of exposure, meaning most salmon can survive short periods (i.e. hours) of temperatures in the low 20 °C's (Jensen and Servizi 1977). However, chronic (>96hrs) exposure temperature threshold's for adult Pacific salmon are between 18-23°C, although there is considerable variation between species and populations (i.e. stocks for most salmon populations) (Eliason et al., 2011; Lee et al., 2003; Macdonald et al., 2010; McCullough, Sturdevant, & Hicks, 2001; Richter & Kolmes, 2005). The magnitude of the temperature related mortality in Fraser sockeye salmon has exceeded 50% for many populations in recent years (Martins, Hinch, Cooke, & Patterson, 2012), with a further concern that these percentages are predicted to rise with the increase frequency and duration of extreme temperature events associated with future climate change (Hague et al., 2011)(Reed et al. 2011)

In this study, I used a simulation approach to compare performance of mixed stock and terminal fisheries under time-varying temperature-dependent en route mortality. Simulation modelling allows for evaluation of management strategies without socioeconomic and population impacts that can result from trial and error management strategies (Kerr, Cadrin, & Secor, 2010; Walters, 2007). I used the Fraser River Salmon Management Model (FRSMM)(Carter, 2014) to simulate the impact of shifting fisheries from lower-river, mixed-stock fisheries to upstream single-stock terminal fisheries for the Fraser River sockeye. The FRSMM is an individual based, spatially explicit simulation model with discrete time steps and spatial increments that simulates directional migration through river systems by a collection of salmon stocks. Individual based modeling (IBM) allows for integration of the increased complexity of individuals, and environmental experiences (DeAngelis & Grimm, 2014). The IBM design within FRSMM allows multiple fish within each single stock to experience different temperatures and fisheries along the migration route according to their individual migration path, entry timing, and speed. The significant degree to which temperature-dependent mortality and capture risk vary across time and space makes individual based modeling superior to traditional models for evaluating mixed-stock fisheries targeting migrating species.

Fraser River sockeye salmon (*Oncorhynchus nerka*) have been harvested throughout their return spawning migration by Indigenous peoples for millennia, and in commercial gauntlet fisheries in the marine approaches and lower-river (Figure 1) for over a century (Harris, 2001; Nelson & Turris, 2004). Since 1995 there has been an increasing occurrence of en route mortality events in the Fraser River (Cooke et al., 2004; Patterson et al. 2016)) that have been linked to rising river temperatures (Hinch et al., 2012; Macdonald et al., 2010). Migration temperatures experienced by Summer run sockeye have increased by 2°C since 1953, leading to more frequent and more severe en route mortality events (Figure 2)(Cooke et al., 2004; Patterson, Cooke, et al., 2016; Patterson et al., 2007). Summer run sockeye are the third run timing group to arrive in the Fraser River, usually from early August through September, and (Patterson et al., 2007). The timing of river entry will determine the temperature regime they are likely to experience and will, therefore, influence their upstream survival (Martins et al., 2011). Similarly, the stock-composition of the Summer run group in a given year will determine how vulnerable the group as a whole will be to high temperature events (Eliason et al., 2011; Martins et al., 2011).

Population-specific differences in thermal tolerance exist among the major sockeye stocks in the Fraser River (Eliason et al., 2011; Lee et al., 2003) and they are consistent with the reported stock-specific en route mortality estimates (Martins et al., 2011). The physiological mechanisms behind the population-specific differences in migration success include temperature mediated effects on swimming performance, oxygen consumption, and cardiorespiratory physiology (Eliason et al., 2011; Farrell et al., 2008; Lee et al., 2003). As river temperature approaches and exceeds optimal migration temperature for sockeye, the probability of survival is reduced with increase duration of exposure (Farrell et al., 2008). In response to the expected en route mortality estimates, fishery managers have adopted a precautionary management approach, to protect co-migrating stocks with differing mortality risks (Hinch et al., 2012; Patterson, Hague, Scroggie, & Benner, 2016). For example, the Pacific Salmon Commission (PSC) uses Management Adjustment (MA) models to forecast en route mortality in Fraser sockeye using water temperature as the primary indicator (Cummings, Hague, Patterson, & Peterman, 2011; Macdonald et al., 2010; PSC, 2016).

Using the FRSMM I simulated lower-river, mixed-stock and upper-river terminal fisheries of Fraser River Summer run sockeye with multiple combinations of river temperature, fixed target harvest levels (tied to run size), run timing (i.e. river entry timing), stock compositions (i.e. relative abundance of stocks within Summer run group aggregate), and harvest timing. River temperature, target harvest, run timing, and stock composition are states of nature that cannot be controlled by fishery managers, but are included here to test sensitivity of management performance. Harvest rate, timing and location are management actions that can be controlled. I fixed the harvest plan to be based on current Canada-US Pacific Salmon Treaty (PST) management goals for Summer run sockeye, but did not provide compensation for predicted en route mortality via a Management Adjustment model (PSC, 2019b). My results are applicable to other sources of measurable en route mortality, including disease, water quality, discharge, fishing related incidental mortality, extended freshwater residence, and barriers to migration. I will test how mortality, catch, and escapement are impacted by the management tactics under the four states of nature, providing a toolbox for fishery managers considering spatial changes to fixed total harvest strategies in light of expected increases in en route mortality.

Background: Fraser River Sockeye Management

Fraser River sockeye salmon returns vary in abundance, timing, and stock composition between years (DFO, 2014; Knudsen, 1999; PSC, 2017). Annual Return estimates for Fraser River sockeye have varied from 500,000 in 2019 to 30 million in 2010 (PSC, 2017, 2019a). Fraser River sockeye are managed in four run-timing groups, categorized by river-entry timing: Early Stuart (June/July), Early Summer (July/August), Summer (August/September), and Late (September/October). The four run timing groups (RTGs) are aggregations of geographically distinct stocks that have similar return migration timing into the Fraser River (DFO, 2011; PSC, 2017). Test fisheries in the marine approaches and freshwater entry, as well as Lower-river hydroacoustic estimates, allow for genetic stock identification of the individual stocks that are used to infer the RTG arrival timing and abundance, allowing for active management of individual run-timing groups in-season to account for inter-annual variability in abundance (Beacham et al., 2004; DFO, 2013, 2016)

The diversity of harvest locations, gear types, and objectives of the various fish harvesting groups complicates the management of Fraser River sockeye and makes changes to harvest locations difficult (Cohen, 2012). Fraser River sockeye salmon migrating from the north Pacific are commercially harvested by seine, gillnet, and troll fisheries in the Johnstone and Juan de Fuca straits (Figure 1), and finally by gillnet fisheries in the lower-river below Mission (PSC, 2017). Indigenous groups harvest Fraser River sockeye in commercial economic opportunity (EO) fisheries, and in food social and ceremonial (FSC) fisheries. Indigenous harvesters utilize seines, gillnets, hook and line, beach seines, fish-wheels, dip-nets, or weirs from the marine approach areas through the lower-river and into the terminal spawning areas (Harris, 2001; Indigenous Foundations, 2009). Rod and reel recreational fisheries targeting Fraser sockeye access fish in the marine approach areas, estuary, and throughout the lower Fraser River, as well as some specific near-terminal locations.

Under the PST, 16.5% of the Fraser River Sockeye total allowable catch (TAC) is allocated to the US for harvest by Treaty Indians, commercial harvesters, and recreational fishers (DFO, 1999). TAC is the surplus to spawning and FSC requirements that is allocated for harvest. The in-season management responsibility for Fraser River sockeye salmon is transferred annually from the DFO to the Fraser River Panel (FRP), a

Canada-United States organization tasked with managing according to the PST (DFO, 2014). In accordance with the PST, the FRP manages to three ordered objectives: (1) obtain spawning escapement goals by stock or stock grouping; (2) meet international harvest allocation as defined under the Treaty; and (3) achieve domestic objectives (Figure 3) (PSC, 2019b). Each country is responsible to how it achieves their domestic objectives within their respective share for each RTG. The Canadian domestic allocation policy objectives outline that, after conservation needs are met, priority access is for Indigenous FSC, with the remaining harvest of sockeye allocated to recreational (5%) and commercial fisheries (95%) (DFO, 1999).

Total allowable catch, or TAC, is estimated based on the highest exploitation rate (total catch ÷ total return) available from two methods, Low Abundance Exploitation Rate (LAER) and Total Allowable Mortality (TAM) rule. If the RTG size is below the lower TAM threshold, the LAER is used, otherwise the exploitation rate is calculated from the TAM rules. The TAM includes harvest and an optional portion of en route mortality decided on by the Fraser River Panel. Under medium to high abundance, and assuming no en route mortality, the PSC calculates the allowable harvest from specific TAM rules specific for each RTG (DFO, 2011). The forecasted abundance of the returning run (or run size) is the main factor in deciding the percentage of TAM for each RTG. The TAM rules have upper and lower thresholds that limit the amount of harvest allowed given an estimated return size (Figure 4). Below the lower threshold (red line in Fig. 4) the exploitation rate is limited to the LAER allowing for incidental harvest of more abundant co-migrating stocks or species, and test fishing. The LAER has varied between an equivalent 10-20% TAM. Between the lower and upper thresholds (red and green lines in Fig. 4) exploitation rate increases with the run size until the upper reference point is reached (generally 50-60% TAM). Above the upper threshold (green line) the exploitation rate is capped to ensure robustness against uncertainty in population dynamics and differing productivity of stocks within the aggregate RTG (DFO, 2011). Given that the TAM values are set at the RTG level the proportional rate of harvest is applied equally to the stocks within the RTG; the expectation is that larger stocks will be harvested more numerically than smaller stocks.

The TAM is designed to account for all fish removed by commercial, recreational, and Indigenous fisheries, as well as the number of fish likely to die during the return migration (i.e., en route mortality). En route mortality is forecasted using management adjustment (MA) models (Macdonald et al., 2010). The MA models are multiple linear regression models with environmental and biological predictor variables (ie. temperature, discharge, run timing) based on historical discrepancies between lower-river and spawning ground estimates (DBE's in Figure 2). Pre-season and in-season predictor variables are forecasted to calculate the proportion of the run that is likely to die en route. The TAM is split into TAC and MA, functionally the MA allocation is part of the unfished spawning escapement allocation. In theory, the MA proportion is the proportion of fish allowed to naturally escape that will die during the migration if the MA forecast was perfect.

The stock specific differences in en route loss are not currently included in the MA modeling approach, as mortality is estimated at the RTG level. However, we know from telemetry studies that stock specific differences exist in en route mortality (Martins et al., 2011), likely driven by the stock-specific differences in physiological tolerance to high temperatures (Eliason et al., 2011). Therefore, the proportional composition of stocks making up the RTGs is important when estimating annual stock-specific differences in en route mortality. For example, the Fraser River Summer RTG has significant differences in thermal tolerance between the four main stocks (Chilko, Quesnel, Late Stuart, and Stellako), with Chilko having the higher thermal tolerance.

The RTG arrival timing to Mission, the upper boundary of the mixed-stock lower-river fishery, is forecasted pre-season and adjusted in-season with updated assessment information and used to inform harvest timing. Harvest timing for a specific RTG can vary based on the relative abundance of stocks within a RTG, as well as the degree of overlap with neighbouring RTGs.

2. Methods

FRSMM structure

The FRSMM model is a hybrid boxcar/individual-based, spatially explicit simulation model. Adult migrating sockeye are represented as aggregated groups known as “boxcars” and as individual fish. The boxcars represent aggregate abundances grouped by stock, timestep, and reach. The individual-based component structure allows for fine-scale spatial and temporal evaluation of en route mortality and for exposure to differing temperatures and harvest levels for each stock within a RTG. The FRSMM uses a 12-hour timestep, sufficient to capture the detail used in temperature readings (24 hr mean) and harvest rates (24 hr estimates). The spawning migration route is split into 10 km reaches, starting at Mission, BC (Fig. 1); 10 km is shorter than the distances attributed to each of the river temperature stations. The FRSMM model uses a biological mechanism of temperature-induced mortality that can simulate a large range of outcomes, given environmental and harvest conditions.

MA models currently used by the DFO generate single mortality estimates for each RTG (i.e. not stock) using a single temperature value to represent the temperatures experienced by the RTG over their entire migration. This is problematic for terminal fisheries as harvest targets single stocks that experience unique temperature exposures (Morrison & Foreman, 2005). The MA models are fit using past data that is prone to large assessment errors and constrained by the range of environmental conditions that fish have historically experienced. This latter constraint does not allow for the simulation of more extreme water temperatures that are likely to be faced by sockeye salmon as river temperatures continue to increase due to climate change (Hague et al., 2011).

FRSMM uses BOTS (BOTS are Objects for Tracking States) to track the simulated physiological state of approximately 1000 individual migrating salmon per stock within a RTG. These physiological states link the water temperature conditions experienced during migration with acute and cumulative impacts of temperature conditions on movement and survival. For example, the temperature that would be experienced by a migrating sockeye in each reach and timestep is recorded by the

BOTS. The recorded temperature is then used in the mortality model to assess the likelihood of survival and, in turn, movement.

BOTS follow the same movement calculations as the boxcars of fish they represent (Carter, 2014). The number of BOTS for each stock is continually assessed to ensure that (i) BOTS are present in the same locations and time steps as the aggregate boxcar component, reflecting the conditions experienced by the entire stock and (ii) the number of BOTS is sufficient (min 1000 bots) to provide statistically reliable values for survival and migration rates at each location and time step. BOTS experience similar mortality risks as the aggregate boxcars but, when BOTS die, new BOTS are spawned from the survivors as needed to meet conditions (i) and (ii).

Mortality Calculation

The FRSMM removes, or 'kills', fish stochastically, based on short- and long-term temperature-related mortality functions. Separate sub-models are used to calculate survival probabilities for short-term and long-term exposure, which are then combined using an additive model to represent the expected total mortality. Moment method estimators are then used to parameterize a Beta-Binomial distribution from which the total number of fish dying of temperature-related mortality is drawn for each stock within each time step and reach.

The short-term temperature exposure mortality model uses a median lethal dose (LD-50) set at the temperature associated with 90% of the stock-specific aerobic scope (Figure 5)(Eliason et al., 2011). Aerobic scope represents the difference between resting and maximal metabolic rates; this relationship changes with water temperature in a dome shaped pattern (Figure 5) (Pörtner & Farrell, 2008). The optimum temperature (Topt) represents the apex of the aerobic scope curve, and the optimal temperature for aerobic swimming ability. The percentage of aerobic scope required to complete migration is uncertain and likely varies by stock and year (Hague et al. 2011). Previous efforts to estimate the amount of aerobic scope required to complete migration for Weaver Creek (110km migration) and Gates (364 km migration) sockeye (Late RTG stocks), suggested 50% and 80% respectively (Farrell et al. 2008; Hague et al. 2011). The four main Summer RTG stocks, the focus of this evaluation, have a much more energetically demanding migration than both of these lower Fraser River stocks;

therefore, LD-50's of 80% and 90% of the aerobic scope were assessed for this model. The final selection of 90% was chosen as it provided a better match with post-season estimates of en route mortality from tagging (Martins et al. 2012) and stock assessment estimates (i.e. DBE's Macdonald et al. 2010) (Figure 5 dotted line). This value is consistent with Eliason et al. (2011) suggestion that 90% of the aerobic scope could limit migration. In the FRSMM, the median lethal dose represents the temperature required to kill 50% of the population at a given time and location. Among the stocks used in the model, Chilko has the highest temperature (20.7°C) at 90% of aerobic scope, followed by Stellako and L. Stuart (19°C), and Quesnel (18.5°C). Stellako and L. Stuart have the same aerobic scope relationship because of the inability to separate these two stocks using genetic methods.

The long-term temperature exposure mortality model uses a median lethal dose of 500-degree days of accumulated temperature exposure as the long-term LD-50 for all stocks (Wagner et al., 2005). Adult sockeye salmon exposed to high water temperatures for prolonged periods have higher mortality rates (Hinch et al., 2012). This increased mortality is incorporated into the FRSMM using the long-term LD-50, based on accumulated thermal units (ATU) or degree days. The use of ATU's as a mortality input is supported by the connection between ATU's and development of Parvicapsula minibicornis parasite (Wagner et al., 2005). Severity of infection in sockeye was shown to increase and swim performance decreased after 450 accumulated degree days (Wagner et al., 2005). Further work by Bradford et al. (2010) confirmed the central role of degree-days in pathogen development and associated mortality for Fraser sockeye salmon (Bradford, Lovy, & Patterson, 2010). 500 degree-days was selected for all stocks with a standard deviation (SD) of 50 degree-days.

The form of the short-term S and long-term L temperature exposure mortality sub models are identical (Eq 1), differing only by the values of parameters μ and σ. A cumulative normal distribution function is used to represent a sigmoidal dose-response relationship between the probability of death and temperature exposure, i.e.,

$$F\left(T_{S,t,b,i} \mid \mu_{S,i}, \sigma_{S,i}\right) = \int_{x=-\infty}^{x=T_{S,t,b,i}} \exp\left[-\left(x-\mu_{S,i}\right)^2 \Big/ 2\sigma_{S,i}^2\right] \qquad \text{Equation 1}$$

For short-term exposure, $T_{S,t,b,i}$ is the average temperature at time t, computed over the last eight time steps (i.e. 96hr) for BOT b, in stock i, given the short-term LD-50 temperature value μ and standard deviation σ (μ and σ are obtained from Eliason et al. 2011), which controls the steepness of the curve. For long-term exposure, $T_{L,t,b,i}$ is the accumulated degree days for the BOT b, in stock i , given the long-term LD-50 degree day value μ and standard deviation σ.

Short-term and long-term mortality rate estimates are assumed to be additive (Equation 2) and weighted equally (i.e., w = 0.50), giving a mortality rate $m_{b,i,t}$ for each timestep and reach, i.e.,

$$m_{b,i,t} = w\Phi\left(T_{S,t,b,i} \mid \mu_{S,i}, \sigma_{S,i}\right) + \left(1 - w\right)\Phi\left(T_{L,t,b,i} \mid \mu_{L,i}, \sigma_{L,i}\right) \qquad \text{Equation 2}$$

The mortality rate of the aggregate boxcar stock i at each time step t and reach r is computed using the mean mortality rate $\bar{m}_{i,t,r}$ and variance $\tau^2_{i,t,r}$ computed for all BOTS of the same stock present in that reach and time step.

Method-of-moment estimators are used to calculate the Beta distribution function shape $\hat{\alpha}$ (equation 3) and scale $\hat{\beta}$ (equation 4) parameters, i.e.,

$$\hat{\alpha}_{i,t,r} = \bar{m}_{i,t,r}\left[\frac{\bar{m}_{i,t,r}\left(1 - \bar{m}_{i,t,r}\right)}{\tau^2_{i,t,r}} - 1\right] \qquad \text{Equation 3}$$

$$\hat{\beta}_{i,t,r} = \left(1 - \bar{m}_{i,t,r}\right)\left[\frac{\bar{m}_{i,t,r}\left(1 - \bar{m}_{i,t,r}\right)}{\tau^2_{i,t,r}} - 1\right] \qquad \text{Equation 4}$$

Finally, the total number of fish dying from temperature-related mortality $D_{i,t,r}$ for each stock and timestep is randomly drawn from a Beta-Binomial distribution (Equation 5),

$$D_{i,t,r} \sim Beta - Bin\left(N_{i,t,r}, \hat{\alpha}_{i,t,r}, \hat{\beta}_{i,t,r}\right) \qquad \text{Equation 5}$$

Movement Calculation

Fish movement in the FRSMM is calculated using a stochastic movement sub-model, parameterized with stock-specific movement rates. It is assumed that adult sockeye in the Fraser River cannot swim upstream more than 80 km (8 reaches) in a 12-hour period (one timestep). This is a reasonable assumption, given that 80 km/12-hr equates to 3 body lengths per second swim speed for a 60 cm sockeye sustained over 12 hours, which is likely not achievable, especially against typical Fraser River flows. We further assume that movement is independent of river temperature (Hanson et al. 2008). The number of fish that move to each of the subsequent reaches is calculated in three steps as follows:

Step 1.

A cumulative probability of transitioning to each of the eight following reaches or staying at the current reach Θ_i is calculated using an ordered multinomial logit model (equation 6). In the model, probability of transition Θ_i is calculated using *y*, the average response variable, and σ_j, the spread parameter for each transition between reaches, known as the cut point c_i. The response variable is the stock-specific movement rate for the reach R and the spread parameter is the number of possible reaches a fish can move to. Transition probabilities must be greater than or equal to zero, less than or equal to one, and must sum to one, ensuring all fish stay within the 9 possible reaches.

$$Q_i = \begin{cases} 0 & i = 0 \\ 1 - \operatorname{logit}^{-1}\left(\left(y - c_i\right)/s_J\right) & 1 < i < R \\ 1 & i = R \end{cases}$$

Equation 6

Step 2.

The probability of moving from reach r to reach r + c_i is computed for each location *i,* by taking the differences between the cumulative probabilities (Equation 7).

$$q_i = \begin{cases} Q_i & i = 1 \\ Q_i - Q_{i-1} & i > 1 \end{cases}$$

Equation 7

Step 3.

Finally, the number of fish $N_{t,r}$ in reach r at time t is re-distributed in t + 1 among the nine potential reaches r to r + c_9 by a random draw from a multinomial distribution (Equation 8).

$$N_{t+1,r:r+c_9} \sim \text{Multinomial}\left(N_{t,r}, q_{r:r+c_9}\right) \qquad \text{Equation 8}$$

Model Inputs and Scenarios

The FRSMM uses past temperature data, sockeye migration timing, stock-specific physiology, stock composition data, and simulated harvest data to estimate mortality. This section outlines how the environmental and harvest scenarios are developed and the sources of information that are used. The summer RTG was selected as it has the highest and most consistent harvest of the 4 run timing groups, experiences high thermal exposure, and is of interest for implementing a terminal fisheries (Patterson, per. comm.).

River Temperature Scenarios

The environmental scenarios were selected to provide an example of a low, medium, and high temperature year. The deciding metric for what constitutes a low, medium, and high temperature year was the mean water temperature measured for the Fraser River near Qualark Creek during the 31-day period centered around the historical average peak migration date for the Summer RTG. This water temperature monitoring station and thermal exposure metric is used by the DFO for in-season sockeye management. Eight temperature stations along the migratory path of the summer RTG (Figure 1) were used to represent the thermal exposure of migrating sockeye. Temperature data were provided by the Water Survey of Canada and the DFO Environmental Watch Program (EWP)(Hague, Patterson, & Macdonald, 2008). The 2011 water temperature profile was selected as the low temperature year, 2006 as the medium year, and 2013 as the high year. The daily Fraser River temperature profiles near Qualark Creek for the three scenarios are shown in Figure 6. The 2013 temperature profile has 14 days with a mean temperature above 20°C and 9 days above 21°C. The simulated arrival timings used in this project are lined up with this warm period, making it the warmest migration condition recorded on the Fraser River.

Migration Speed, Run Size, Arrival Timing, and Stock Composition

Stock-specific movement rates were calculated from radio-tagging studies tracking sockeye salmon movement rate by study reach (e.g. Hanson et al. 2008; Martins et al. 2011). Stock-specific movement rates were converted to kilometers per day for each group of reaches aligned with the tagging experiment (Table 1). The movement rates were then converted in the model from kilometers per day to reaches per timestep by dividing the number of kilometers per day by the speed ratio, 20.

Run size/target harvest, run timing, and stock composition inputs were varied to model the true impact of stock-specific en route mortality outputs on different harvest scenarios. The simulated run sizes and compositions used in the model were based on years 2014 (large run) and 2016 (small run). The three arrival timings were tested based on the historical mean run timing for the last 25 years (PSC 2019), with uncertainty included as historical mean plus and minus one standard deviation. The stock-specific spread, or the number of days the stock takes to migrate past a given point was calculated using the historical average over the last 25 years. The proportion of the four stocks that make up the RTG (i.e. proportion of Chilko fish in the Summer RTG) was taken from the 2014 and 2016 years, however, the sensitivity of differing stock proportion was tested by applying the 2014 proportion to 2016 and vice versa. Testing the sensitivity to differing stock proportions is important, as thermal tolerance and movement speed differs between stocks.

Harvest Scenarios

In my analysis, simulated harvest is impacted by run size/target harvest, harvest timing and harvest location. Harvest location and timing can both be controlled by managers, however, under the TAM rules, harvest level is fixed to the run size. A harvest rate of .75 per reach per timestep was used to meet the TAC targets for the large and small run sizes. TAC targets were calculated by subtracting the TAM from the total run size. To allow for comparison between temperature scenarios, a MA was not used when creating the TAC. Based on the TAM rules, approximately 50% TAM was allocated (Figure 4) for the large run size in 2014 and a 10% TAM was allocated for the small run size in 2016, with the latter following a conservative LAER. The TAC for the terminal fisheries was created by dividing the aggregate TAC by the stock proportion of the RTG (table 2). Harvest locations for the downstream mixed-stock fishery were between Mission and Hope (7 reaches). The upper-river terminal harvest locations used were the last seven reaches before the end of the migration route for each stock. Seven reaches were used at the terminal harvest locations to allow for harvest of the TAC over a distance equal to that of the lower-river harvest location. The three harvest timing scenarios were centered on the RTG arrival time, five days before, and five days after the peak RTG arrival timing. As there is uncertainty in arrival timing to Mission for the RTG in season, harvest timing sensitivity was tested to account for possible estimation error, and to assess the sensitivity of the results to harvest timing under perfect information (Hague & Patterson, 2007). The impact of stock composition was tested by using two different relative proportions of the RTG for the Chilko stock (Table 2). The proportion scenarios, (1) high relative proportion Chilko stock (74% of RTG) and (2) low relative proportion Chilko stock (40% of RTG) are the actual proportions from 2014 and 2016. The proportion of Chilko has greater relative impact than Stellako, Quesnel and Late Stuart as mortality levels are highly sensitive to Chilko as it has the highest thermal tolerance.

Simulated in-season harvest decision rules that excluded predicted losses were used to test the impact of moving harvest location. For lower-river harvest, fish are removed from the harvest reaches until the combined TAC is obtained. For the upper-river harvest scenarios, fish removal is managed separately for each terminal harvest area. In the model, upper-river harvest is stopped at each terminal area once the stock-specific TAC is reached. At the end of each time step, the total catch is summed and, if the TAC is realized, the harvest rate for the next timestep is changed to zero, otherwise the fishery remains open. As catch is summed at the end of each timestep, the cumulative catch can exceed the TAC by up to one timestep per RTG or stock. This reflects the current management framework, as catch cannot be counted instantaneously. In reality, equivalent harvest ability may not be feasible between upper and lower river harvest locations due to differing gear types and river conditions.

Model Summary/Sensitivities

The base FRRSMM model evaluates the impact of harvest location on en route mortality, spawning escapement, and catch proportions under different water temperature and run size/target harvest scenarios. All model runs used to assess the interaction between harvest location and temperature-based mortality were based on 90% aerobic scope and 500-degree day values for the short-term and long-term LD50 parameters, respectively. Response variables including en route mortality, spawning escapement, and catch are presented as percentages of the initial run size for the Summer RTG in each scenario, where run size is defined as the abundance of fish entering the river past Mission, BC. Mortality is defined as the proportion of the run size that is removed due to temperature-related mortality, catch rate is the proportion of the run size that is removed by harvest, and spawning escapement rate is the remaining proportion of fish that survive the migration after mortality and catch are removed. Sensitivity analyses are included for arrival timing and relative stock composition to account for the natural annual variability. Sensitivity to harvest timing and harvest targets via changes to run size, were tested to highlight how management decisions impact mortality, spawning escapement and catch.

3. Results

Base Model: Variable Temperature and Target Harvest

The FRSMM model was able to accurately reflect the expected temperature dependent mortality predictions; en route mortality increased, and spawning escapements decreased with each progressively warmer year under the no harvest scenario (Fig. 6). Mortality under the no harvest scenario was 13% (each number reflects the proportion of loss relative to the original total run size) under the low temperature scenario, 53% under the middle temperature scenario, and 86% under highest temperature scenario. Low and average temperature years represent historical DBE’s while the high temperature year represents an extreme yet realistic scenario. The low and high temperature years provide good examples of a typical thermograph profile with a gradual rise, peak, and fall (Fig 9). The high temperature year is based on the temperature profile for 2013, however, the Summer run sockeye arrived late that year, avoiding the peak of the temperature profile. The results presented were robust to the stochastic elements of the FRSMM with a 0.9% coefficient of variation between 50 model runs with the same parameters.

The highest in-river temperatures resulted in the largest increases in en route mortality for terminal versus lower-river harvest scenarios. For example, under the highest temperature year, the terminal harvest tactic resulted in a 49% increase in en route mortality for the 50% target harvest and 11% increase in mortality for the smaller 10% target harvest when compared to the lower river harvest tactic (Figure 6). In comparison, the increase in mortality under the low temperature year was less, with a 4% increase for the 50% target harvest and no increase for the 10% target harvest strategy. As expected, the increase in en route mortality for terminal harvest under high temperature scenarios can be explained by the higher proportion of the RTG being susceptible to en route mortality when lower-river harvest does not occur.

Spawning escapements were also influenced by harvest location and temperature-related mortality. The most extreme example was a reduction in spawning escapement from 12% for lower-river harvest to 0% for terminal harvest, under high exploitation (target harvest 50%) and high temperature scenario (Figure 6). The spawning escapement for terminal harvest was 6% lower than the spawning escapement for lower river harvest under the low temperature scenario for the large run size/high target harvest. For the small run size/low target harvest, there was a 4% reduction in spawning escapement for terminal harvest vs lower river under the highest temperature scenario, and no difference in spawning escapement between harvest locations at the low temperature scenario.

The largest reduction in catch occurred under the highest temperature scenario, which resulted in a 37% decrease in catch for the large run size/high target harvest, and a 6% decrease in catch for the small run size/low target harvest under the terminal harvest scenario relative to mixed stock (Figures 6). There was no difference in catch between terminal and lower-river harvest at low temperatures. At high temperatures, the abundance of fish surviving en route mortality that are available for harvest at terminal locations is reduced, resulting in lower catch.

Sensitivity to Arrival Timing

The changes in en route mortality and spawning escapement under the no harvest scenario show sensitivity to timing independent of harvest. En route mortality decreased and spawning escapements increased with the three successive arrival timing from early to late under the no harvest scenario, with the notable exception of the medium temperature year. The spawning escapement and mortality patterns can be explained by viewing where the arrival timing falls on the temperature profile (Figure 9). The medium temperature year thermograph does not exhibit a significant peak and fall during the three arrival timings, resulting in muted differences between timings (Figure 8). If Early arrival timings arrive at or before the peak river temperature there is increased exposure to high temperature, whereas if late arrival timings arrive at or after the peak temperatures there is lower temperature exposure.

Under lower-river harvest scenarios, mortality remained lower and spawning escapement remained higher than under the terminal harvest scenarios for all combinations of run size/target harvest, water temperature, and run timing, except the low harvest rate /low temperature scenario were they were equal. The impact of arrival timing and harvest location on catch was particularly acute for the high temperature and large run size/high target harvest scenario (Figure 7). Moving to terminal harvest at high temperature with a large run size/high target harvest resulted in a 46% decrease in catch for early arrival timing, 37% for the mean arrival timing, and 27% for the late arrival when compared to lower river harvest.

Sensitivity to Lower-River Harvest Timing

En route mortality is sensitive to lower-river harvest timing shifts of 5 days either side of the centered date. Model outputs showed lower mortality and higher catch proportions when lower-river harvest timing removes a portion of the RTG likely to be exposed to the highest temperatures for the longest period. In the high temperature scenario, early lower-river harvest had the lowest en route mortality, followed by centered, then late. Increased mortality for late lower-river harvest when compared to early lower-river harvest is due to the declining temperature profile as harvesting early removes the section of the run that would have been exposed to the highest temperatures for the longest period. As lower-river harvest takes place before the majority of en route mortality, there is little change in catch between harvest timings. However, mortality and spawning escapement vary by as much as 13% and 11% respectively under the large run size/high target harvest, high temperature scenario between early and late harvest timings (Figure 10). Differences between lower-river harvest timings are negligible in low temperature and small run size/low target harvest scenarios. This is explained by the decreased impact of temperature-related mortality and catch when temperature is low and run size/target harvest is low.

Sensitivity to Chilko Relative Proportion

Under the no harvest scenario, there was a large difference between mortality and escapement under the two relative proportions. As expected, the lower the proportion of Chilko the higher the en route mortality under the no harvest scenario (Figure 11). Lower relative proportion of Chilko (40% vs 74% of the RTG) increased the mortality and decreased spawning escapements under both harvest location scenarios at medium and high temperatures.

Sources of uncertainty

Apart from the sensitivities mentioned above, there is uncertainty in mortality and movement parameters. The short-term mortality parameters are based on swim experiments with small sample sizes while the long-term mortality parameters are estimated based on infection severity studies and are not stock specific. The movement speed parameters may also lead to uncertainty as the speed at which the fish moves impact the duration of temperature exposure. Movement rates can be impacted by discharge levels, arrival timing, and barriers to migration.

4. Discussion

The continued challenge for fishery managers to achieving spawning escapement targets while maximizing harvest is going to become even more difficult with the expected rise in temperature dependent en route mortality. I have found that moving a fixed-catch target based on a stock-aggregate from a lower-river mixed-stock fishery to a stock-selective upper-river terminal fishery will increase mortality and lower spawning escapement under all conditions that increase en route mortality. This intuitive, yet hitherto unquantified result, has important implications for spatial and temporal harvest planning under increased likelihood of en route mortality as a result of climate change (Hague et al. 2011; Reed et al. 2011). This conclusion is particularly pertinent for salmon fishery managers considering moving catch allocations to terminal reaches, as allocation cannot be transferred without reducing spawning escapement or overall catch under a management approach that does not account for en route mortality (e.g. Macdonald et al., 2010) and/or adjust to provide stock-specific aggregate targets. My research shows that not only would moving catch impact the ability to meet spawning escapement targets, but it would also reduce the total available catch for harvesters. En route mortality is impacted by the states of nature, water temperature, arrival timing, and stock composition, and the corresponding effect on spawning escapement and catch is further influenced by the management options applied, harvest location, harvest timing and harvest rate.

The no harvest tactic showed how water temperature, run timing, and stock composition impacted en route mortality and spawning escapement independent of harvest tactics. As the only harvest independent source of mortality in the FRSMM is water temperature, the states of nature impact on overall mortality are linked to either an increase in temperature exposure for individual fish with varying exposure levels. The three increasing water temperature scenarios when modeled with no harvest resulted in the expected increase in mortality and decrease in escapement with each increasing temperature scenario. Arrival timing varied between each temperature scenario as expected, with increased mortality for arrival timings aligned with the higher temperatures in a given years thermograph, this is consistent with previous correlational analysis examining the influence of run timing on estimates of en route loss (Hague and Patterson 2007). Similarly, stock composition impacted mortality and escapement through differing the tolerance of individual fish to thermal exposure based on stock origin and timing. The high survival for Chilko relative to Stellako, Quesnel, and Late Stuart is consistent with empirical telemetry studies (Martins et al. 2011). Overall, the FRSMM no harvest mortality results align with previous studies that show that substantial en route mortality takes place between entering the river and reaching the spawning grounds and is linked to extended exposure to high in-river temperature conditions (Cooke et al. 2004; Macdonald et al. 2010; Patterson et al. 2007).

My simulations of lower-river mixed-stock fisheries and upper-river terminal fisheries, under various levels of temperature related en route mortality, show how moving harvest both spatially and temporally would impact spawning escapement. Using an individual-based model allowed me to simulate spatially varying harvest strategies, and the impact of temperature for stocks with differing thermal mortality risks. River temperature as expected was shown to have a significant impact on mortality, escapement and catch. River temperature is forecasted pre-season and in-season and can provide a signal as to how large the impact will be on migrating fish, and whether harvest mitigation is necessary (Hague & Patterson, 2007; Morrison & Foreman, 2005). Stock composition and arrival timing can be highly variable between return years, however, through the use of historical data and in-season test fisheries estimates can be forecasted (Michielsens & Cave, 2019). Recent advances increasing the speed and accuracy of genetic stock identification (GSI) and parental based tagging (PBT) could also allow for in-season forecasting of arrival timing and stock composition when paired with test fisheries located in marine areas (Beacham et al., 2017).

The results of this study can be used to highlight where managers have flexibility to adjust harvest locations and timing. When presented with a given forecast of river temperature, arrival timing, stock composition and run size, managers have three main factors that can be controlled to meet escapement targets while maximizing catch - harvest location, harvest timing, and target harvest level. A low temperature forecast allows flexibility in harvest location, and timing, with harvest being the primary source of mortality. In a case where high temperature is expected, managers can restrict harvest to lower-river areas, time harvest to remove fish migrating through the peak of the thermograph and reduce harvest to provide a buffer for the expected en route morality. As shown in figure 6, lower-river harvest results in higher spawning escapements while maintaining catch rates. The difference between lower-river and terminal harvest can be conceptualized as harvesting fish before they can succumb to temperature mortality versus harvesting only the survivors. While potential survivors are also harvested in lower-river fisheries, terminal fisheries miss the opportunity to harvest en route mortalities. This concept can be further extended to lower-river harvest timing. By harvesting an aggregation of fish likely to be exposed to the highest temperatures, the fishery is selectively removing the fish with the highest en route mortality risk. Inversely, harvest of a single segment of the run could lead to the removal of genetic diversity that would allow for adaptation to increasing river temperatures (Hard et al., 2008). River temperature is one of the most important driver for en route mortality that managers can consider when moving harvest followed by stock composition and arrival timing.

The current MA model strategy (not evaluated in this analysis) was originally developed as a method of reaching spawning escapement targets based on adjustments to lower-river or marine fisheries. The MA models in their current form cannot be used for single-stock terminal fisheries as the models only provide RTG level estimates and do not explicitly consider spatial or temporal variation in en route mortality (Macdonald et al. 2010). Previous work has shown that en route mortality does reduce the potential harvestable surplus in single stock terminal harvest relative to lower river harvest, and will result in lower catch if stock-specific spawning escapement targets are to be met (Freshwater et al., 2020). For a single-stock fishery to be successful it would require a shift in management scale that would provide in-season estimates of escapement and either negligible or robustly forecasted en route mortality between the estimate location and spawning grounds. In Bristol Bay, Alaska, U.S.A. mixed-stock marine approach fisheries utilize a terminal escapement system for management. Sockeye are counted as they enter their discrete river systems near the fishery location; a system that does not have an in-season mechanism to account for en route mortality(Hilborn & Hilborn, 2019; Hilborn et al., 2003). A modified version of the single-stock escapement enumeration could be used for managing Fraser River sockeye by enumerating fish between the locations of significant en route mortality and the terminal harvest location. For example, enumerating fish through the use of sonar or a fence near the spawning ground would allow for a spawning escapement estimate that will not need adjustment for en route mortality. With a robust spawning escapement estimate, excess to the spawning escapement target can be harvested.

I used the Fraser River summer run sockeye as a case study; however, my findings are applicable to other migrating salmon population with the likelihood of a significant en route mortality event. The Skeena, Nass, Columbia, Somass, Willamette, and Klamath Rivers, as well as the Bristol Bay systems are all examples of systems with lower-river mixed-stock harvest that have the potential for increased en route mortality under climate change and increased industrial activity (Bowerman et al., 2016; Snyder, 2014). My methodology and results show that analysis of the impacts on mortality, spawning escapement, and catch should be completed prior to shifting harvest location and harvest timing in any system with expected high en route mortality.

The results of this study are based on the key assumption that fisheries continue being managed in season to a catch and escapement target at the stock aggregate (RTG) level with a fixed total harvest strategy. For the Fraser system, this assumption is supported by the recent renewal and implementation of a 10 year PST agreement (PSC, 2019c) between Canada and United States. Canada does have some flexibility in management of the Canadian proportion of the TAC allocation, however, shifting of harvest to terminal locations would impact First Nations, recreational, and commercial catch objectives. To implement a terminal fishery management framework for any given mixed-stock system, terminal catch levels would have to be set at the stock level, which requires either a robust en route mortality estimation method that is stock specific or terminal location stock assessment program that can respond quickly to fluctuations in abundance. The feasibility for terminal fisheries to harvest at levels comparable to lower-river fisheries has not been explored and may not be possible for some river systems with high en route mortality. To estimate temperature related en route mortality by stock in-season, predictions of river temperature, arrival timing, stock composition, and stock-specific thermal tolerance are needed (e.g. Hague et al. 2011). River temperature is difficult to predict pre-season and in-season (Hague and Patterson 2014). Current models for forecasting in-season river temperatures in the Fraser only provide one forecast for the entire watershed (Morrison & Foreman, 2005). Arrival timing estimates are available in-season for the RTG, however, accurate stock-specific estimates of arrival timing are not available in-season. Stock specific thermal tolerance estimates have been created for some stock (e.g. Eliason et al. 2011) but are currently only utilized by the FRSMM to estimate mortality, and the performance as a forecasting model has not been evaluated. The FRSMM would also require in season forecasts for the migration routes of each stock being evaluated. The MA models currently used to predict en route mortality have poor stock-specific fits (Patterson et al. 2019). In order to implement terminal fisheries under the current management structure, the above information sources would need to be improved, and models with the ability to forecast en route mortality would have to be created and tested (Holt and Peterman 2006). This study relies on the assumption that Fraser sockeye harvest will continue to be managed in aggregate run timing mixed stocks.

It is important to recognize that the FRSMM results are not meant to be an accurate prediction tool under the current parameters. For the purpose of this project, the FRSMM creates mortality using a biological mechanism and allows for testing of harvest plans under possible scenarios. To improve the FRSMM, further research should be done on the long- and short-term mortality parameters, and on the integration of other possible sources of en route mortality, including fishing related incidental mortality, unreported catch, high discharge, and predation (Patterson et al. 2017a,b).

The approach used in this project does not consider some of the other negative effects of mixed-stock fisheries, such as by-catch of other co-migrating species / or populations that might be at risk of extirpation. For example, there are 28 Chinook, Sockeye, Coho, and Steelhead salmon populations in the Fraser river that have been assessed as endangered or threatened that have the potential to be intercepted by fisheries targeting summer run sockeye (SARA, 2021). Terminal fisheries have the advantage of being able to be more selective at targeting fish from an isolated spawning ground. Under the aforementioned scenarios, the conservation of the other co-migrating species or stocks would need to be considered a priority objective over catch. For a scenario with co-migration of stocks at risk of extirpation, further work could take place to use a combination of upper-river and lower-river fisheries, balanced through optimization to allow for maximizing catch while reducing the impacts of bycatch. If the co-migrating species or stock is listed under the species at risk act (SARA), which prohibits the killing, harming, harassment or capture of listed species, terminal harvest could allow for harvest without subjecting the listed species to fishing impacts ("Species at Risk Act," n.d.). However, there is currently no salmon species in Canada listed under SARA, despite numerous populations being assessed as endangered or threatened. Recent legislative changes to the Fisheries Act in Canada that deal with legal requirements to rebuild depleted stocks will likely play a role in assessing the trade-offs between mixed-stock and terminal fishery planning are part of the legal requirement for rebuilding stocks. As such, I recommend a fulsome evaluation of the risks and benefits of both mixed stock and terminal fisheries.

The sensitivity of all of the harvest controls on en route mortality has important implications for future adaptation of different stocks to climate change. Fishing induced selectivity has led to changes in sockeye size, run timing, productivity, and fitness (Cox & Hinch, 1997; Hard et al., 2008). Reed et al. (2011) warn that selectivity in Fraser River sockeye fisheries "might counter or swamp climate-induced selection pressures, potentially limiting the capacity of populations to keep evolutionary pace with changes in climate" (2011). To assess the impact of moving harvest location on selectivity, more research is necessary. Both upper and lower-river fisheries have the potential to cause fishing induced selectivity, depending on gear type, harvest rate, harvest duration, and harvest timing. Terminal harvesting targets the fish that survive the migration, which have the highest value for adaptation. Therefore, it could be argued that any fish that survive a high temperature year are more valuable for future population resilience than a random selection of fish captured in the lower river. The terminal harvest scenarios led to a decrease in the number of fish surviving the migration and harvest to spawn. Inversely, as shown in the lower-river harvest scenarios a single component of the population is disproportionately reduced, and that component may have fish with adaptations to survive thermal exposure by adjusting arrival timing. In Chinook and pink salmon for example, there is good evidence of a correlation between arrival timing and genetic markers within a population (Fukushima & Smoker, 1997; Prince et al., 2017). There is speculation that lower-river harvest of late-run Fraser sockeye has led to changes in the arrival timing (Cooke et al., 2004). Given how sensitive mortality is to temperature extremes and the importance of arrival timing to determine thermal exposure risk, any directed harvest of a group selected for thermal tolerance or of a component of the run adapted to a given run timing could reduce the diversity and the capacity of stocks to adapt to future warming trends.

My research has shown that mixed-stock lower-river fisheries are preferable when the objective is to meet escapement targets while maximizing catch and minimizing mortality under the current management objectives. However, terminal fisheries may be considered as an alternative to, or in combination with lower-river fisheries for meeting alternative objectives such as protecting endangered populations, reducing fishing-induced selection pressures, allowing for upper-river fishing, and allowing for addressing specific Indigenous management concerns.

Recreational and commercial fishers in the interior Fraser River region have requested harvest opportunities for more upper-river locations to allow for tourism, and local fishing opportunities. Terminal harvest could meet the objectives of upper-river recreational and commercial fishers, however, it would result in significantly decreased catch for lower-river recreational and commercial fishers under the current management scheme in warm years with high en route mortality.

Indigenous groups and experts in Indigenous law contend that Indigenous peoples have the rights to manage their own fisheries or to enter into co-management agreements (Walter, Gonigle, & Mckay, 2000). Upper-river terminal fisheries would allow for more proactive management by those individual Indigenous Groups residing in terminal areas, as spawning escapement surveys on grounds can give near-real time estimates of abundance and allow for harvest of surplus (Atlas et al., 2020). Such fisheries currently take place at salmon enhancement facilities (e.g. Weaver spawning channel) under the term Escapement to Surplus Spawning Requirements or ESSR (DFO IFMP – 2019). Upper-river harvest may additionally allow for some indigenous people to increase harvest in their traditional territories. Shifting to an local management system would likely lead to a loss in overall catch, decrease in economic catch value, and would likely require changes to current domestic allocation policy and potentially PST, resulting in a likely reduction of lower-river or marine harvest by recreational, commercial and indigenous harvesters (Routledge, 2001). The results of this analysis are based on a maximum catch objective, and may not reflect FSC harvest objectives, future work could be done to include various Indigenous nations objectives into the analysis.

Next steps for this project include, the use of the FRSMM for in season management of Fraser River sockeye, a management strategy decision analysis and further improvement of the mortality and movement parameters. Further work on model fit and evaluation could allow the FRSMM to be used as a pre/in season management tool. Managers could test potential management strategies and/or determine the optimal strategy for meeting fishery objectives given different forecasts of temperature, run size, arrival timing, and stock composition. A structured decision analysis could be developed to evaluate harvest tactics with the inclusion of temperature, run size, run timing, and stock composition probabilities and forecast uncertainty (Figure B.1.). The mortality and movement rates could be improved by using the data collected in association with the Big Bar slide monitoring project and be used to reduced uncertainty.

The application of the FRSMM model has highlighted the importance of considering en route mortality when evaluating changes to harvest control measures for Fraser River sockeye salmon on spawning escapement and catch goals. Most notable was the impact of changing harvest location from lower-river mixed-stock, to upper-river terminal fisheries, which resulted in increased mortality and decreased escapement under the current management scheme. There was some ability to adjust the temperature related en route mortality via changes in harvest rate and harvest timing. As river temperatures are projected to rise, the frequency of high en route mortality events is expected to increase (Hague et al. 2011). Given the increase in mortality, lower-river fisheries will continue to result in lower mortality and increased spawning escapement when catch is fixed. My results demonstrates that a fixed catch cannot be moved spatially or temporally without impacting mortality and therefore spawning escapement. For Fraser River sockeye fishery managers, lower-river fisheries continue to allow for harvest under increasing temperature scenarios, given the current management framework. The conditions that contribute to low thermal exposure include, low river temperature, late arrival timing, and high proportions of thermally tolerant stocks (ie. Chilko). With increasing levels of en route mortality any attempt to change the harvest location and timing for Pacific salmon will require more quantitative modelling of en route loss to explicitly determine the trade-offs among management objectives.

5. Tables

Table 1 **Stock specific movement rates (km/day) for each segment of the stocks return route (Martins et al., 2011)**

From	To	Chilko	Stellako	Quesnel	Late Stuart
Release	Port Mann	33.3	33.8	36.6	38.2
Port Mann	Mission	37.5	38.1	40.9	43.3
Mission	Harrison	42.1	42.7	45.7	48.5
Harrison	Hope	41.5	41.8	44.7	47.2
Hope	Sawmill	27.1	27.1	29.3	30.9
Sawmill	Thompson	32	32.5	34.8	36.8
Thompson	Kelly	39.4	39.8	42.5	45.1
Kelly	Chilcotin	43.9	44.6	47.6	50.5
Chilcotin	Quesnel		45.6	53	51.8
Quesnel	Naver		27.7		31.4
Naver	Nechako		27.7		31.4
Nechako	Stuart		42.3		47.9
Stuart	Nechako CUs		42.3		
Stuart	Stuart CUs				47.9
Chilcotin	Chilcotin CUs	26.6			

Table 2 **Stock proportions used in the two proportion scenarios, and the stock difference between scenarios. Scenarios one and two are the retrospective estimates from 2014 and 2016, respectively (Maxine Forrest, Pacific Salmon Commission 2018.**

Stock	Scenario 1 Proportions (Low Chilko) 2014 Proportion	Scenario 2 Proportions (High Chilko) 2016 Proportion	Difference
Chilko	40.3%	74.4%	34.1%
Stellako	17.1%	11.8%	5.3%
Quesnel	36.4%	2.7%	33.7%
Late Stuart	6.2%	11.1%	5.0%

6. Figures

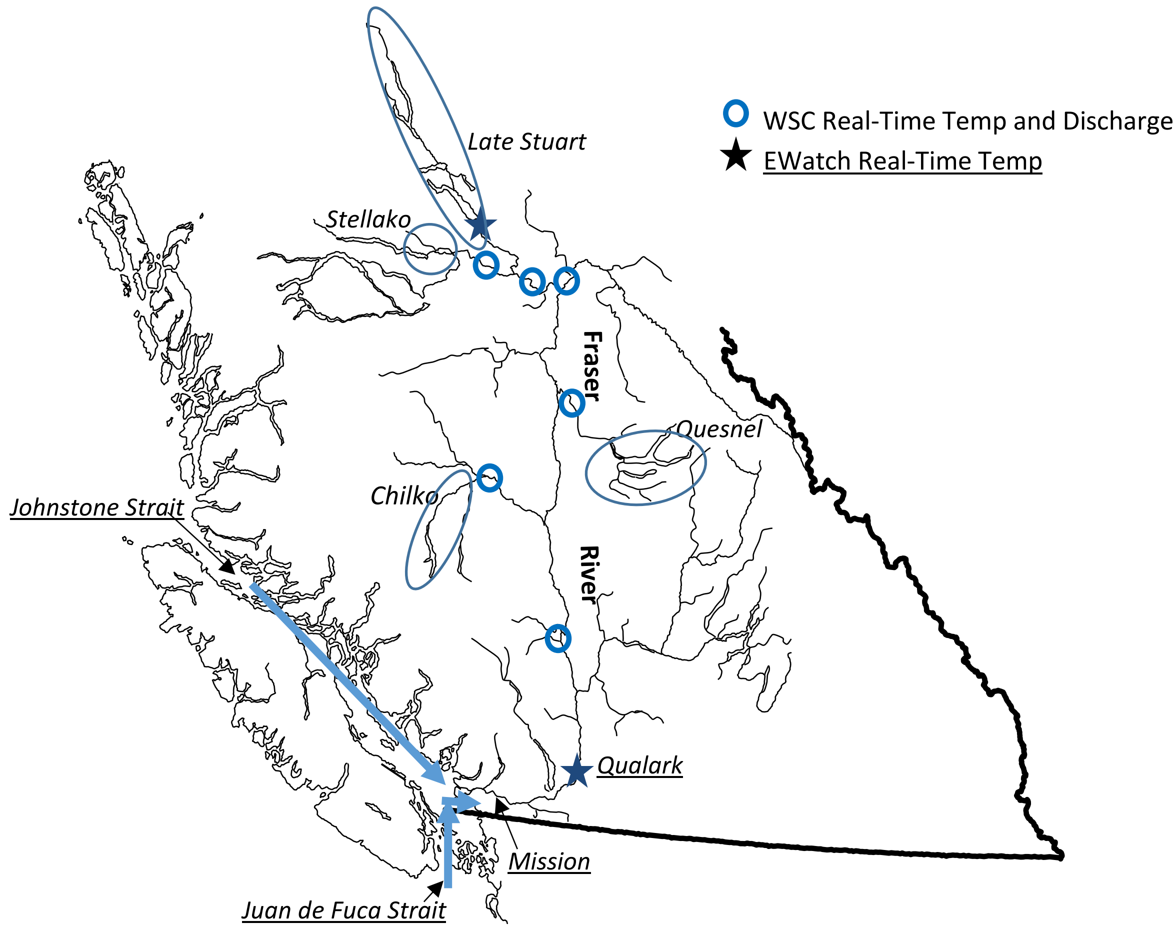

Figure 1 **Fraser River Watershed – Gauntlet fisheries take place along the migration route, denoted by the blue arrows. Circles represent potential terminal harvest location, natal spawning and freshwater rearing locations for the four major summer stocks.**

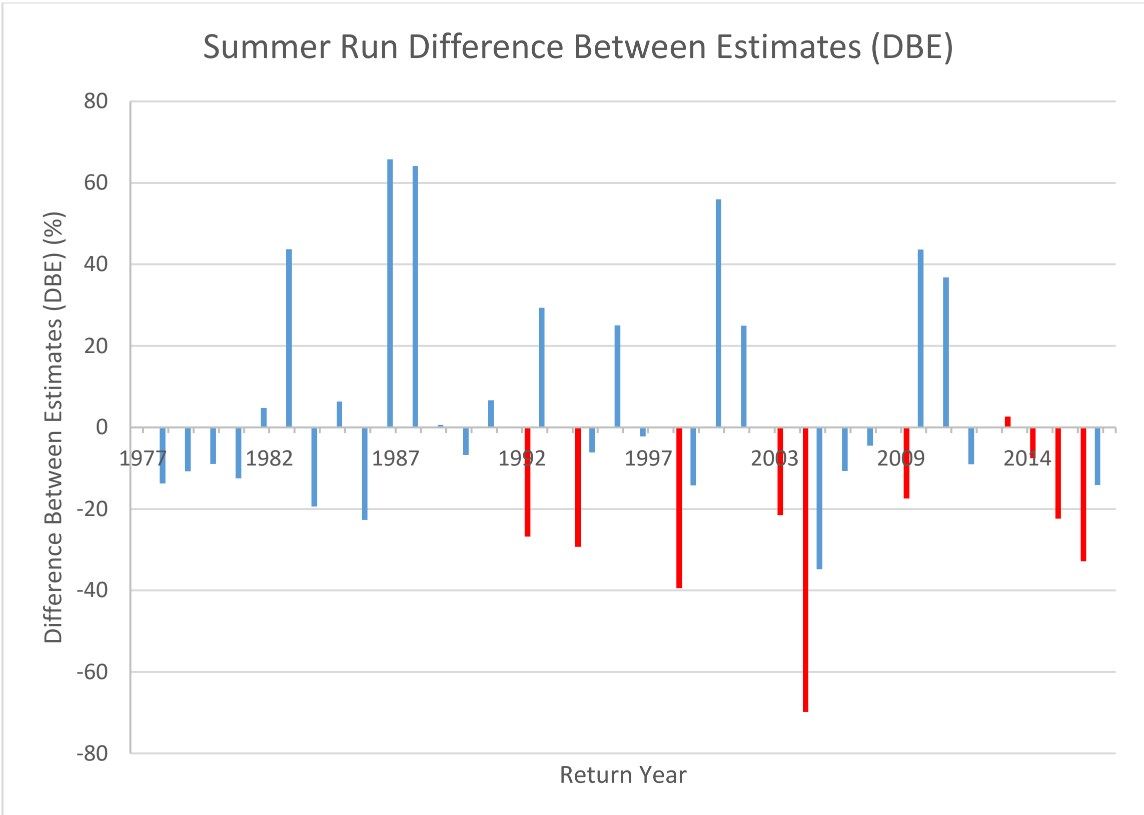

Figure 2 **Summer run sockeye Difference Between Estimates (DBE) 1977-2017, red bars represent years with a mean run timing centered 31-day average Hope temperature above 19˚C (Maxine Forrest, Pacific Salmon Commission 2018). DBE values are the difference between estimated return sizes between the Mission Hydro acoustic facility and the spawning grounds after accounting for in-river catch. Negative values occur when spawning ground estimates are less than Lower-river counts, indicative of en route mortality and/or unaccounted catch. Positive values occur when more fish are estimated on the spawning grounds than the Lower-river, suggesting potential assessment errors in spawning, Lower-river escapements, and/or catch.**

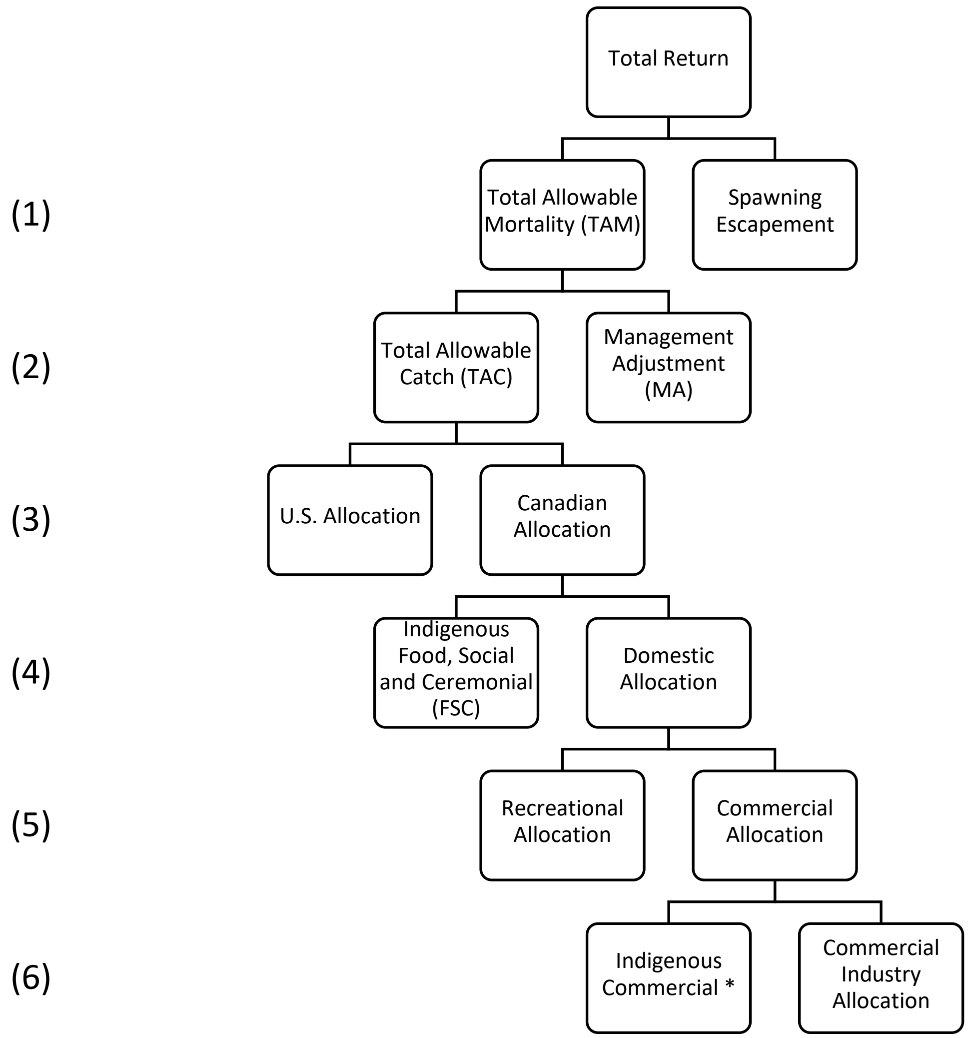

Figure 3 **Fraser River sockeye target allocations – (1) The required spawning escapement target is subtracted from the total run-timing specific return, leaving the total allowable mortality (TAM). (2) The Management Adjustment (MA) is subtracted from the TAM, giving the Total Allowable Catch (TAC). (3) The TAC is split between the US (16.5%) and Canada (83.5%) following the PST allocation agreement. (4) Canadian allocation is split between Indigenous FSC and domestic allocation, with the priority going to Indigenous FSC. (5) Domestic allocation is than split between the recreational (5%) and commercial sectors (95%). (6) Finally the commercial allocation is split between Indigenous Commercial and Commercial fisheries with the priority going to Indigenous fisheries. * Indigenous commercial fisheries can include economic opportunity fisheries (EO), demonstration fisheries, and excess salmon to spawning requirement fisheries (ESSR). (PSC, 2019c)**

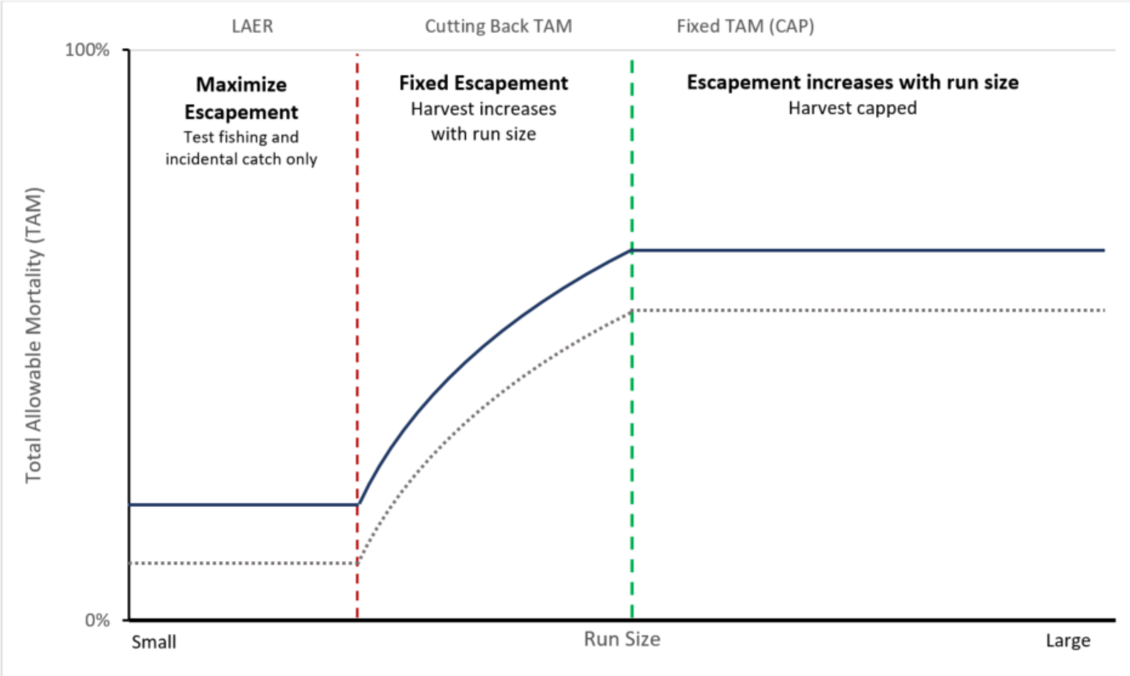

Figure 4 Shape of the Total Allowable Mortality (TAM) rule without MA (blue) and with a hypothetical MA (grey). For returns of run timing groups with sizes below the lower threshold (red line) TAM is fixed (10-20%). The TAM level increases with the run size until the upper threshold (green line) is met, above the upper threshold the TAM is capped (50-60%). Run sizes for the lower and upper thresholds are calculated pre-season to account for the differing productivity and forecasted return sizes of the stocks that make up the RTG (DFO, 2018a). The grey line shows the hypothetical exploitation rate that would be required to keep TAM below the blue line under a scenario where there is an en route mortality rate of 10%.

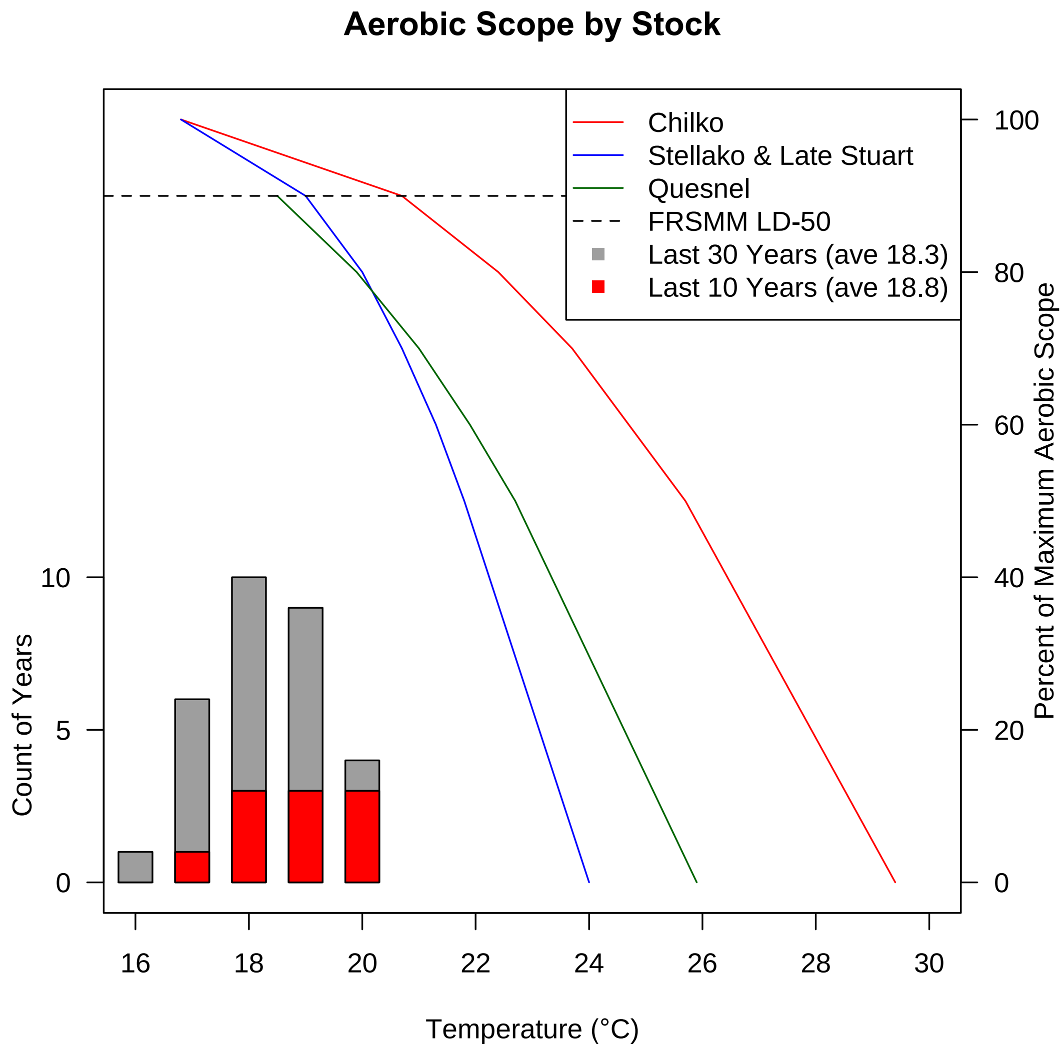

Figure 5 **Percentage of maximum aerobic scope by temperature (°C) for the summer RTG stocks and count of years by average temperature (°C) for the last 30 years (grey) and last 10 years (red). Locations on the lines close to 100% represent the optimal temperature (Topt), where sockeye have their full aerobic scope available. As temperature increases to the critical temperature (Tcrit), the percentage of the available aerobic scope decreases to zero. The Quesnel scope does assign a temperature for 100% of maximum aerobic scobe as here were not enough data points in the Eliason et al. (2011) study. (Modified from Eliason et al., 2011)**

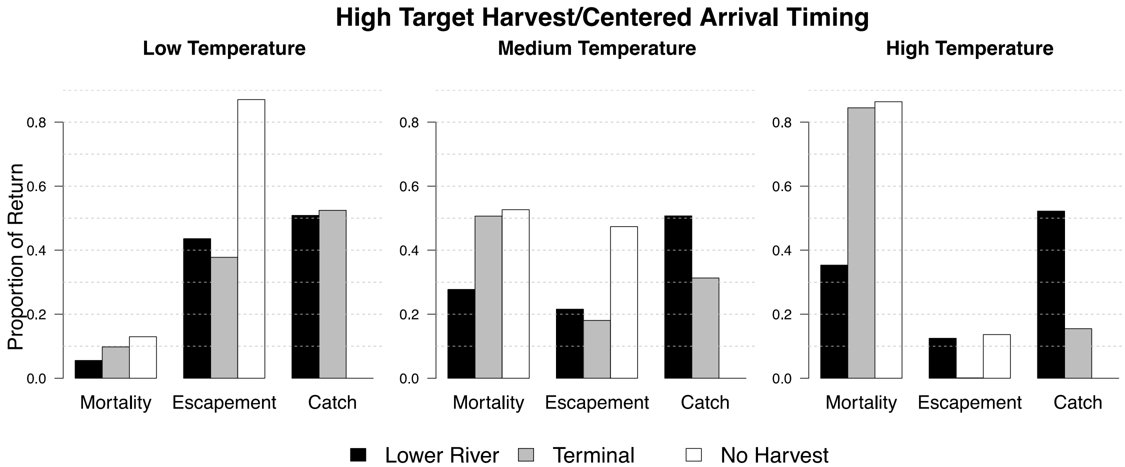

Figure 6 **Low, average, and high temperature scenarios for the high target harvest scenario. Mortality is increased, spawning escapement is decreased, and catch is decreased under the high temperature scenario. Differences between lower-river and terminal harvest are magnified with high temperature.**

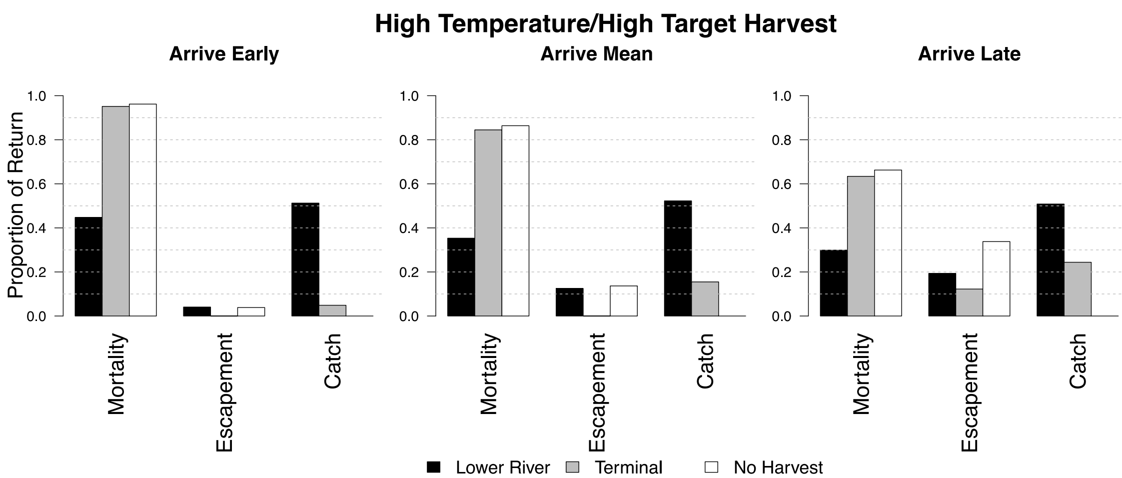

Figure 7 **High target harvest, high temperature sensitivity to arrival timing. Mortality decreases, spawning escapement increases, and catch increases from early arrival to late.**

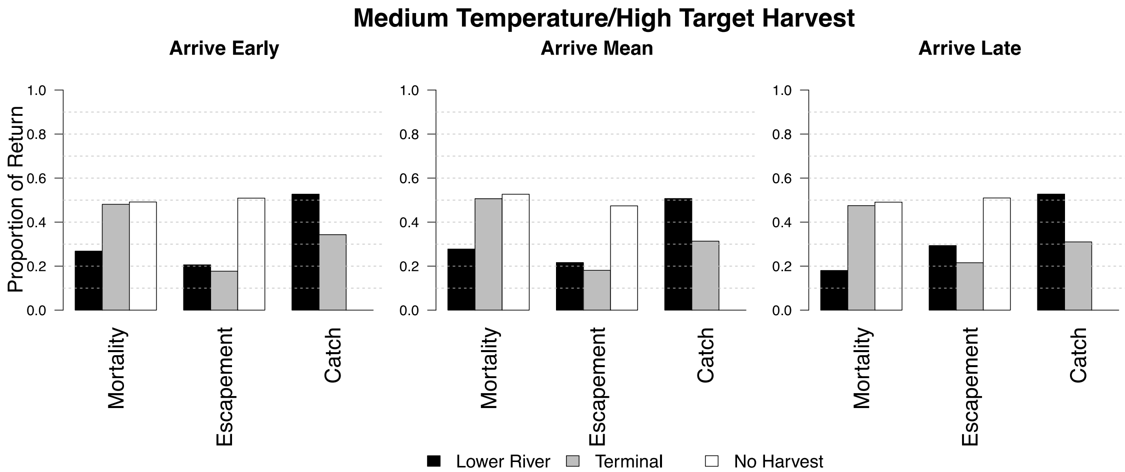

Figure 8 **Medium temperature/high target harvest sensitivity to arrival timing. Mortality is stable between run timings due to the flat thermograph (Figure 9)**

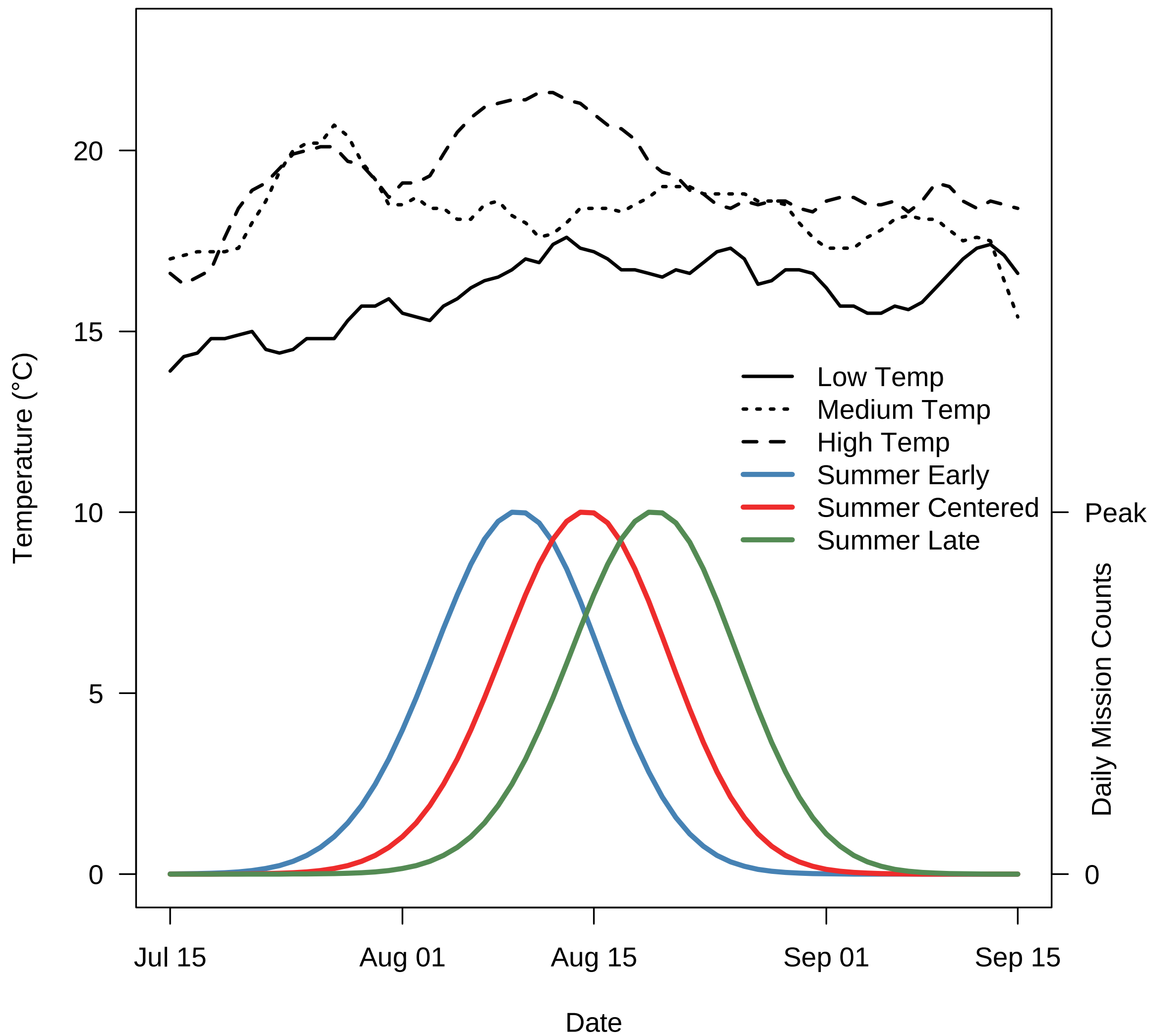

Figure 9 **Daily mean temperatures recorded for the Fraser River near Qualark Creek in 2006, 2011 and 2013, representing average, low and high thermograph years, respectively; the lines at the bottom represent the early, centered, and late return distributions used in the FRSMM model.**

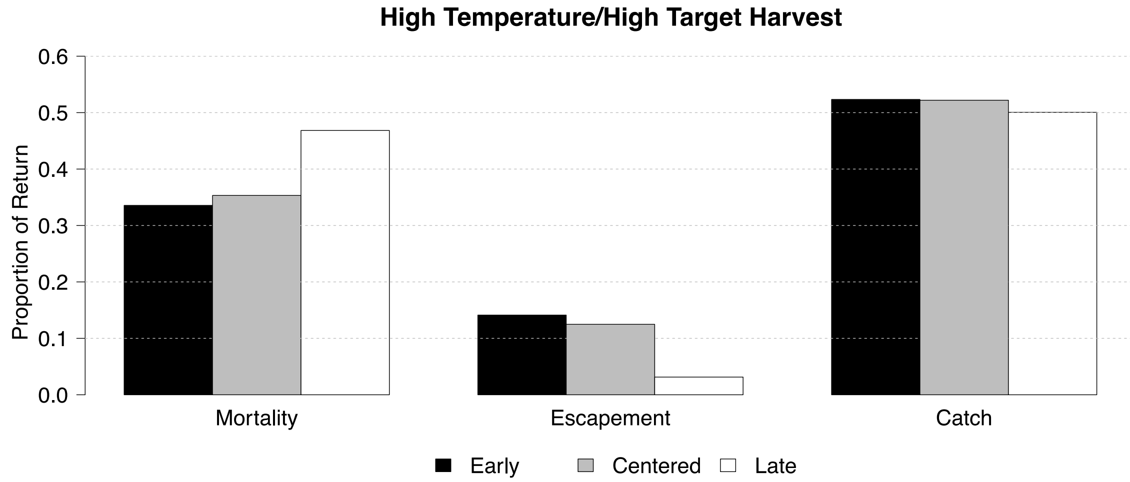

Figure 10 **High temperature/high target harvest sensitivity to lower-river harvest timing. Mortality increases and spawning escapement decreases from early and centered to late lower-river harvest timing**

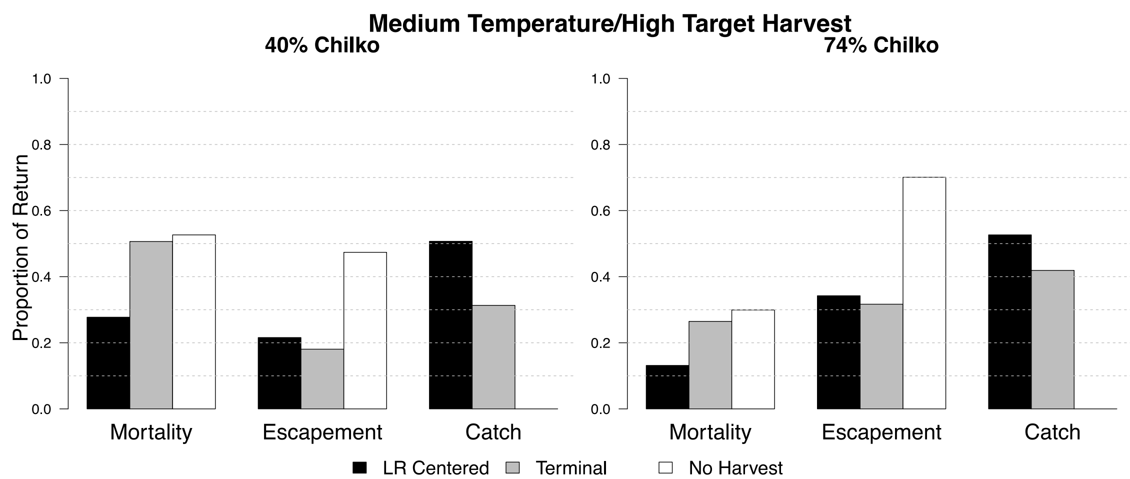

Figure 11 **RTG composition 40% Chilko compared with 74% Chilko for medium temperature/large run size. With a lower proportion Chilko, as shown on the left, mortality is higher and the differences between lower-river and terminal harvest are increased.**

References

Atlas, W. I., Ban, N. C., Moore, J. W., Tuohy, A. M., Greening, S., Reid, A. J., … Connors, K. (2020). Indigenous Systems of Management for Culturally and Ecologically Resilient Pacific Salmon (Oncorhynchus spp.) Fisheries. *BioScience*. https://doi.org/10.1093/biosci/biaa144

Barnett, H. K., Quinn, T. P., Bhuthimethee, M., & Winton, J. R. (2020). Increased prespawning mortality threatens an integrated natural- and hatchery-origin sockeye salmon population in the Lake Washington Basin. *Fisheries Research*, *227*, 105527. https://doi.org/10.1016/j.fishres.2020.105527

Beacham, T. D., Lapointe, M. F., Candy, J. R., McIntosh, B., MacConnachie, C., Tabata, A., … Withler, R. E. (2004). Stock Identification of Fraser River Sockeye Salmon Using Microsatellites and Major Histocompatibility Complex Variation. *Transactions of the American Fisheries Society*, *133*(5), 1117–1137. https://doi.org/10.1577/t04-001.1

Beacham, T. D., Wallace, C., Macconnachie, C., Jonsen, K., McIntosh, B., Candy, J. R., … Withler, R. E. (2017). Population and individual identification of coho salmon in british columbia through parentage-based tagging and genetic stock identification: An alternative to coded-wire tags. *Canadian Journal of Fisheries and Aquatic Sciences*, *74*(9), 1391–1410. https://doi.org/10.1139/cjfas-2016-0452

Bowerman, T., Keefer, M. L., & Caudill, C. (2016). Pacific Salmon Prespawn Mortality: Patterns, Methods, and Study Design Considerations. *Fisheries*, *41*(12), 738–749. https://doi.org/10.1080/03632415.2016.1245993

Bradford, M. J., Lovy, J., & Patterson, D. A. (2010). Infection of gill and kidney of Fraser River sockeye salmon, Oncorhynchus nerka (Walbaum), by Parvicapsula minibicornis and its effect on host physiology. *Journal of Fish Diseases*, *33*(9), 769–779. https://doi.org/10.1111/j.1365-2761.2010.01178.x

Bradford, M. J., Lovy, J., Patterson, D. A., Speare, D. J., Bennett, W. R., Stobbart, A. R., & Tovey, C. P. (2010). Parvicapsula minibicornis infections in gill and kidney and the premature mortality of adult sockeye salmon (Oncorhynchus nerka) from Cultus

Lake, British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*(4), 673–683. https://doi.org/10.1139/F10-017

Budy, P., Thiede, G. P., Bouwes, N., Petrosky, C. E., & Schaller, H. (2002). Evidence Linking Delayed Mortality of Snake River Salmon to Their Earlier Hydrosystem Experience. *North American Journal of Fisheries Management*, *22*(1), 35–51. https://doi.org/10.1577/1548-8675(2002)022<0035:eldmos>2.0.co;2

Carter, J. (2014). *Using Stock-Specific Thermal Physiology to Simulate In-River Mortality of Fraser River Sockeye Salmon*. Simon Fraser University.

Cohen, B. (2012). *The Uncertain Future of Fraser River Sockeye*. Ottawa.

Cooke, S. J., Hinch, S. G., Farrell, A. P., Lapointe, M. F., Jones, S. R. M., Macdonald, J. S., … Van Der Kraak, G. (2004). Abnormal Migration Timing and High en route Mortality of Sockeye Salmon in the Fraser River, British Columbia. *Fisheries*, *29*(2), 22–33. https://doi.org/10.1577/1548-8446(2004)29[22:amtahe]2.0.co;2

Cox, S. P., & Hinch, S. G. (1997). Changes in size at maturity of Fraser River sockeye salmon [Oncorhynchus nerka (1952-1993) and associations with temperature. *Canadian Journal of Fisheries and Aquatic Sciences*, *54*(5), 1159–1165. https://doi.org/10.1139/f97-009

Cummings, J. W., Hague, M. J., Patterson, D. A., & Peterman, R. M. (2011). The impact of different performance measures on model selection for fraser river sockeye salmon. *North American Journal of Fisheries Management*, *31*(2), 323–334. https://doi.org/10.1080/02755947.2011.562750

DeAngelis, D. L., & Grimm, V. (2014). Individual-based models in ecology after four decades. *F1000Prime Reports*, *6*. https://doi.org/10.12703/P6-39

DFO. (1999). *AN ALLOCATION POLICY FOR PACIFIC SALMON A New Direction: The Fourth in a Series of Papers from Fisheries and Oceans Canada*.

DFO. (2011). Guidelines for applying updated methods for assessing harvest rules for Fraser River sockeye salmon (Onchorhynchus nerka). *Canadian Science Advisory Secretariat*, (June 2011), Rep. 2010/070. Retrieved from http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

DFO. (2013). *Integrated Biological Status of Fraser River Sockeye Salmon (Oncorhynchus nerka) Under the Wild Salmon Policy*.

DFO. (2014). Management of Fraser River Sockeye Fisheries | Fisheries and Oceans Canada, Pacific Region. Retrieved April 10, 2018, from http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especes/salmon-saumon/sock_mgmt-gest_smonrouge-eng.html

DFO. (2016). A Compilation of Operational and Planning Guidelines for the Salmonid Enhancement Program, 119.

DFO. (2018a). *PACIFIC REGION FINAL INTEGRATED FISHERIES MANAGEMENT PLAN SALMON SOUTHERN BC*.

DFO. (2018b). *Wild Salmon Policy 2018 to 2022 Implementation Plan*. Retrieved from http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especes/salmon-saumon/wsp-pss/ip-pmo/docs/ip-pmo-eng.pdf

Eliason, E. J., Clark, T. D., Hague, M. J., Hanson, L. M., Gallagher, Z. S., Jeffries, K. M., … Farrell, A. P. (2011). Differences in thermal tolerance among sockeye salmon populations. *Science*, *332*(6025), 109–112. https://doi.org/10.1126/science.1199158

Farrell, A. P., Hinch, S. G., Cooke, S. J., Patterson, D. A., Crossin, G. T., Lapointe, M. F., & Mathes, M. T. (2008). Pacific Salmon in Hot Water: Applying Aerobic Scope Models and Biotelemetry to Predict the Success of Spawning Migrations. *Physiological and Biochemical Zoology*, *81*(6), 0–000. https://doi.org/10.1086/592057

Forrest, R. E., Holt, K. R., & Kronlund, A. R. (2018). Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: Bias, robustness and trade-offs. *Fisheries Research*, *206*, 259–286. https://doi.org/10.1016/j.fishres.2018.04.007

Freshwater, C., Holt, K. R., Huang, A., & Holt, C. A. (2020). Benefits and limitations of increasing the stock-selectivity of Pacific salmon fisheries. *Fisheries Research*, *226*, 105509. https://doi.org/10.1016/j.fishres.2020.105509

Fukushima, M., & Smoker, W. W. (1997). Determinants of stream life, spawning efficiency, and spawning habitat in pink salmon in the Auke Lake system, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences*, *54*(1), 96–104. https://doi.org/10.1139/f96-258

Gayeski, N. J., Stanford, J. A., Montgomery, D. R., Lichatowich, J., Peterman, R. M., & Williams, R. N. (2018). The Failure of Wild Salmon Management: Need for a Place-Based Conceptual Foundation. *Fisheries*, *43*(7), 303–309. https://doi.org/10.1002/fsh.10062

Godfrey, H., Hourston, W. R., Stokes, J. W., & Withler, F. C. (1954). *Effects of a Rockslide on Babine River Salmon*. Ottawa.

Hague, M. J., Ferrari, M. R., Miller, J. R., Patterson, D. A., Russell, G. L., Farrell, A. P., & Hinch, S. G. (2011). Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology*, *17*(1), 87–98. https://doi.org/10.1111/j.1365-2486.2010.02225.x

Hague, M. J., & Patterson, D. A. (2007). *Quantifying the sensitivity of Fraser River sockeye salmon (Oncorhynchus nerka) management adjustment models to uncertainties in run timing, run shape and run profile*. *Can. Tech. Rep. Fish. Aquat. Sci.* (Vol. 2776).

Hague, M. J., Patterson, D. A., & Macdonald, J. S. (2008). *Exploratory Correlation Analysis of Multi-site Summer Temperature and Flow Data in the Fraser River Basin Canadian Technical Report of Fisheries and Aquatic Sciences 2797*.

Hanson, K. C., Cooke, S. J., Hinch, S. G., Crossin, G. T., Patterson, D. A., English, K. K., … Farrell, A. P. (2008). Individual Variation in Migration Speed of Upriver-Migrating Sockeye Salmon in the Fraser River in Relation to Their Physiological and Energetic Status at Marine Approach. *Physiological and Biochemical Zoology*, *81*(3), 255–268. https://doi.org/10.1086/529460

Hard, J. J., Gross, M. R., Heino, M., Hilborn, R., Kope, R. G., Law, R., & Reynolds, J. D.

(2008). SYNTHESIS: Evolutionary consequences of fishing and their implications for salmon. *Evolutionary Applications*, *1*(2), 388–408. https://doi.org/10.1111/j.1752-4571.2008.00020.x

Harris, D. C. (2001). *Fish, Law, and Colonialism: The Legal Capture of Salmon in British Columbia*. University of Toronto Press.

Hilborn, R. (1985). Apparent Stock Recruitment Relationships in Mixed Stock Fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *42*(4), 718–723. https://doi.org/10.1139/f85-092

Hilborn, R., & Hilborn, U. (2019). *Ocean Recovery: A sustainable future for global fisheries?* Oxford University Press. https://doi.org/10.1093/oso/9780198839767.001.0001

Hilborn, R., Quinn, T. P., Schindler, D. E., & Rogers, D. E. (2003). Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(11), 6564–6568. https://doi.org/10.1073/pnas.1037274100

Hinch, S. G., Cooke, S. J., Farrell, A. P., Miller, K. M., Lapointe, M. F., & Patterson, D. A. (2012). Dead fish swimming: a review of research on the early migration and high premature mortality in adult Fraser River sockeye salmon Oncorhynchus nerka. *Journal of Fish Biology*, *81*(2), 576–599. https://doi.org/10.1111/j.1095-8649.2012.03360.x

Holt, C. A., & Peterman, R. M. (2006). Missing the target: uncertainties in achieving management goals in. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*(12). Retrieved from https://search-proquest-com.proxy.lib.sfu.ca/docview/219329545/fulltextPDF/6518AA87B47F4BC7PQ/1?accountid=13800

Indigenous Foundations. (2009). Aboriginal Fisheries in British Columbia. Retrieved November 22, 2019, from https://indigenousfoundations.arts.ubc.ca/aboriginal_fisheries_in_british_columbia/

Jones, S. R. M., Prosperi-Porta, G., Dawe, S., Blackbourn, J., Taylor, K., Lowe, G., &

Olborn, A. (2004). Proliferative renal myxosporidiosis in spawning coho salmon (Oncorhynchus kisutch) in British Columbia and Washington. *Folia Parasitologica*, *54*, 221–227.

Jónsdóttir, I. G., Marteinsdottir, G., & Campana, S. E. (2007). Contribution of different spawning components to the mixed stock fishery for cod in Icelandic waters. *ICES Journal of Marine Science*, *64*(9), 1749–1759. https://doi.org/10.1093/icesjms/fsm157

Keefer, M. L., Clabough, T. S., Jepson, M. A., Naughton, G. P., Blubaugh, T. J., Joosten, D. C., & Caudill, C. C. (2015). Thermal exposure of adult Chinook salmon in the Willamette river basin. *Journal of Thermal Biology*, *48*, 11–20. https://doi.org/10.1016/j.jtherbio.2014.12.002

Keefer, M. L., Peery, C. A., Daigle, W. R., Jepson, M. A., Lee, S. R., Boggs, C. T., … Burke, B. J. (2005). Escapement, harvest, and unknown loss of radio-tagged adult salmonids in the Columbia River – Snake River hydrosystem. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(4), 930–949. https://doi.org/10.1139/f04-246

Kemp, A. (2018). Terminal Fisheries | Watershed Sentinel. *Watershed Sentinel*. Retrieved from https://watershedsentinel.ca/articles/terminal-fisheries/

Kerr, L. A., Cadrin, S. X., & Secor, D. H. (2010). Simulation modelling as a tool for examining the consequences of spatial structure and connectivity on local and regional population dynamics. *ICES Journal of Marine Science*, *67*(8), 1631–1639. https://doi.org/10.1093/icesjms/fsq053

Knudsen, E. (1999). *Sustainable Fisheries Management: Pacific Salmon*. *Copeia*. https://doi.org/10.1643/0045-8511(2001)001[1174:]2.0.co;2

Larkin, P. A. (1971). Simulation Studies of the Adams River Sockeye Salmon (Oncorhynchus nerka). *Journal of the Fisheries Research Board of Canada*, *28*(10), 1493–1502. https://doi.org/10.1139/f71-230

Lee, C. G., Farrell, A. P., Lotto, A., MacNutt, M. J., Hinch, S. G., & Healey, M. C. (2003). The effect of temperature on swimming performance and oxygen consumption in adult sockeye (Oncorhynchus nerka) and coho (O. kisutch) salmon stocks. *Journal of Experimental Biology*, *206*(1), 3239–3251. https://doi.org/10.1242/jeb.00547

Macdonald, J. S. (2000). *Mortality During the Migration of Fraser River Sockeye Salmon (Oncorhynchus nerka): A Study of the Effect of Ocean and River Environmental Conditions in 1997*.

Macdonald, J. S., Patterson, D. A., Hague, M. J., & Guthrie, I. C. (2010). Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. *Transactions of the American Fisheries Society*, *139*(3), 768–782. https://doi.org/10.1577/T08-223.1

Mace, P. M., & Sissenwine, M. P. (1993). How Much Spawning per Recruit is Enough. In *J.J. Hunt and D. Rivard [ed.] Risk evaluation and biological reference points for fisheries management* (pp. 101–118).

Martins, E. G., Hinch, S. G., Cooke, S. J., & Patterson, D. A. (2012). Climate effects on growth, phenology, and survival of sockeye salmon (Oncorhynchus nerka): a synthesis of the current state of knowledge and future research directions. *Rev Fish Biol Fisheries*, *22*, 887–914. https://doi.org/10.1007/s11160-012-9271-9

Martins, E. G., Hinch, S. G., Patterson, D. A., Hague, M. J., Cooke, S. J., Miller, K. M., … Farrell, A. P. (2011). Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (Oncorhynchus nerka). *Global Change Biology*, *17*(1), 99–114. https://doi.org/10.1111/j.1365-2486.2010.02241.x

McCullough, D. a. (1999). A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon. *Environmental Protection Agency*, (July), 291.

McCullough, D., Sturdevant, D., & Hicks, M. (2001). *Issue Paper 5 Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids Prepared as Part of EPA Region 10 Temperature Water Quality Criteria Guidance Development Project Summary of Technical Literature Examining the P*.

Michielsens, C. G. J., & Cave, J. D. (2019). In-season assessment and management of salmon stocks using a Bayesian time–density model. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(7), 1073–1085. https://doi.org/10.1139/cjfas-2018-0213

Morrison, J., & Foreman, M. G. G. (2005). Forecasting Fraser River flows and temperatures during upstream salmon migration. *Journal of Environmental Engineering and Science*, *4*(2), 101–111. https://doi.org/10.1139/s04-046

Morse, M. R., Kerr, L. A., Galuardi, B., & Cadrin, S. X. (2020). Performance of stock assessments for mixed-population fisheries: the illustrative case of Atlantic bluefin tuna. *ICES Journal of Marine Science*, *77*(6), 2043–2055. https://doi.org/10.1093/icesjms/fsaa082

Nelson, S., & Turris, B. (2004). *The Evolution of Commercial Salmon Fisheries in British Columbia Report to the Pacific Fisheries Resource Conservation Council*.

Patterson, D. A., Cooke, S. J., Hinch, S. G., Robinson, K. A., Young, N., Farrell, A. P., & Miller, K. M. (2016). A perspective on physiological studies supporting the provision of scientific advice for the management of Fraser River sockeye salmon (Oncorhynchus nerka). *Conservation Physiology*, *4*(1). https://doi.org/10.1093/CONPHYS/COW026

Patterson, D. A., Hague, M. J., Scroggie, J., & Benner, K. (2016). *Evaluation and coordination of information useful for predicting en-route loss in Fraser sockeye*.

Patterson, D. A., Hague, M. J., Scroggie, J., Benner, K., Dick, M., Straight, A., … Bass, A. L. (2019). *Evaluation and coordination of information useful for predicting en-route loss in Fraser sockeye*.

Patterson, D. A., Macdonald, J. S., Skibo, K. M., Barnes, D. P., Guthrie, I. C., & Hills, J. (2007). *Reconstructing the summer thermal history for the lower Fraser River, 1941 to 2006, and implications for adult sockeye salmon (Oncorhynchus nerka) spawning migration*.

Patterson, D. A., Robinson, K. A., Lennox, R. J., Nettles, T. L., Donaldson, L. A., Eliason, E. J., … Hinch, S. G. (2017). Canadian Science Advisory Secretariat (CSAS) Review and Evaluation of Fishing-Related Incidental Mortality for Pacific

Salmon, (May), 155. Retrieved from http://publications.gc.ca/collections/collection_2017/mpo-dfo/Fs70-5-2017-010-eng.pdf

Pellett, K., Stiff, H. W., Damborg, J., & Hyatt, K. D. (2015). *A PIT-Tag Based Investigation Into Somass River Adult Sockeye Migration Behaviour In Response To Environmental Conditions, 2010*.

Pörtner, H.-O., & Farrell, A. P. (2008, October 31). Ecology: Physiology and climate change. *Science*. American Association for the Advancement of Science. https://doi.org/10.1126/science.1163156

Prince, D. J., O'rourke, S. M., Thompson, T. Q., Ali, O. A., Lyman, H. S., Saglam, I. K., … Miller, M. R. (2017). *The evolutionary basis of premature migration in Pacific salmon highlights the utility of genomics for informing conservation*. Retrieved from http://advances.sciencemag.org/

PSC. (2016). Primary Duties | Pacific Salmon Commission. Retrieved December 29, 2020, from https://www.psc.org/about-us/structure/secretariat-staff/primary-duties/

PSC. (2017). Report of trhe Fraser River Panel to the Pacific Salmon Commission on the 2016 Fraser River Sockeye Salmon Fishing Season, (October).

PSC. (2019a). *Fraser River Panel Weekly Reports | Pacific Salmon Commission*. Retrieved from https://www.psc.org/publications/fraser-panel-in-season-information/fraser-river-panel-weekly-reports/

PSC. (2019b). Pacific Salmon Treaty. *Gov Docs*. Retrieved from https://www.psc.org/publications/pacific-salmon-treaty/

PSC. (2019c). *Treaty Between the Government of Canada and the Government of the United States of America Concerning Pacific Salmon*. *Pacific Salmon Commision*. Retrieved from http://www.psc.org/

Quinn, T. P., McGinnity, P., & Reed, T. E. (2016). The paradox of "premature migration" by adult anadromous salmonid fishes: Patterns and hypotheses. *Canadian Journal of Fisheries and Aquatic Sciences*. Canadian Science Publishing.

https://doi.org/10.1139/cjfas-2015-0345

Ray, J. D. M., Sethi, S. A., Eiler, J. H., & Joyce, J. E. (2015). Prespawning movements and spawning distribution of sockeye salmon in an urbanizing Alaskan Lake. *Journal of Fish and Wildlife Management*, *6*(2), 472–485. https://doi.org/10.3996/112014-JFWM-083

Ray, R. A., Holt, R. A., & Bartholomew, J. L. (2012). Relationship between temperature and Ceratomyxa shasta -induced mortality in Klamath River salmonids. *The Journal of Parasitology*, *98*(3), 520–526. https://doi.org/10.1645/JP-GE-2737.1

Reed, T. E., Schindler, D. E., Hague, M. J., Patterson, D. A., Meir, E., Waples, R. S., & Hinch, S. G. (2011). Time to Evolve? Potential evolutionary responses of fraser river sockeye salmon to climate change and effects on persistence. *PLoS ONE*, *6*(6). https://doi.org/10.1371/journal.pone.0020380

Richter, A., & Kolmes, S. A. (2005). Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. *Reviews in Fisheries Science*, *13*(1), 23–49. https://doi.org/10.1080/10641260590885861

Ricker, W. E. (1973). Two Mechanisms That Make it Impossible to Maintain Peak-Period Yields From Stocks of Pacific Salmon and Other Fishes. *Journal of the Fisheries Research Board of Canada*, *30*(9), 1275–1286. https://doi.org/10.1139/f73-207

Routledge, R. (2001). Mixed-stock vs. terminal fisheries: a bioeconomic model. *Natural Resource Modeling*, *14*(4), 523–539. https://doi.org/10.1111/j.1939-7445.2001.tb00072.x

SARA. (2021). Species at risk registry. Retrieved April 19, 2021, from https://species-registry.canada.ca/index-en.html#/species?ranges=1&taxonomyId=4&sortBy=commonNameSort&sortDirection=asc&pageSize=10

Satterthwaite, W. H., & Carlson, S. M. (2015). Weakening portfolio effect strength in a hatchery-supplemented Chinook salmon population complex. https://doi.org/10.1139/cjfas-2015-0169

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., & Webster, M. S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature*, *465*(7298), 609–612. https://doi.org/10.1038/nature09060

Scholz, N. L., Myers, M. S., McCarthy, S. G., Labenia, J. S., McIntyre, J. K., Ylitalo, G. M., … Collier, T. K. (2011). Recurrent die-offs of adult coho salmon returning to spawn in Puget Sound lowland urban streams. *PLoS ONE*, *6*(12). https://doi.org/10.1371/journal.pone.0028013

Snyder, S. (2014). Environment: Science and Policy for Sustainable Development Bristol Bay Wild Salmon, Pebble Mine, and Intractable Conflict: Lessons for Environmental Studies and Sciences. https://doi.org/10.1080/00139157.2014.881693

Species at Risk Act. (n.d.). Retrieved January 20, 2020, from https://laws-lois.justice.gc.ca/eng/acts/s-15.3/page-4.html#h-434768

Stephenson, R. L. (2002). *Stock structure and management structure: an ongoing challenge for ICES*. *ICES Marine Science Symposia* (Vol. 215).

Wade, A. A., Beechie, T. J., Fleishman, E., Mantua, N. J., Wu, H., Kimball, J. S., … Stanford, J. A. (2013). Steelhead vulnerability to climate change in the <scp>P</scp> acific <scp>N</scp> orthwest. *Journal of Applied Ecology*, *50*(5), 1093–1104. https://doi.org/10.1111/1365-2664.12137

Wagner, G. N., Hinch, S. G., Kuchel, L. J., Lotto, A., Jones, S. R. M., Patterson, D. A., … Farrell, A. P. (2005). Metabolic rates and swimming performance of adult Fraser River sockeye salmon (Oncorhynchus nerka) after a controlled infection with Parvicapsula minibicornis. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(9), 2124–2133. https://doi.org/10.1139/f05-126

Walter, E., Gonigle, R. M. M., & Mckay, C. (2000). Fishing Around the Law: The Pacific Salmon Management System as a “Structural Infringement” of Aboriginal Rights. *McGill Law Journal*, *45*(I), 264–314.

Walters, C. J. (1975). *Optimal Harvest Strategies for Salmon in Relation to Environmental Variability and Uncertainty About Production Parameters*. Retrieved from http://pure.iiasa.ac.at/424/

Walters, C. J. (2007). Is adaptive management helping to solve fisheries problems? *Ambio*. https://doi.org/10.1579/0044-7447(2007)36[304:IAMHTS]2.0.CO;2

Westley, P. A. H. (2020). Documentation of *en route* mortality of summer chum salmon in the Koyukuk River, Alaska and its potential linkage to the heatwave of 2019. *Ecology and Evolution*, *10*(19), 10296–10304. https://doi.org/10.1002/ece3.6751

Wright, S. (1981). Contemporary Pacific Salmon Fisheries Management. *North American Journal of Fisheries Management*, *1*(1), 29–40. https://doi.org/10.1577/1548-8659(1981)1<29:CPSFM>2.0.CO;2

Appendix A. Supplemental Tables

Table A.1. Early, average and late arrival timing morality, escapement, and catch proportions for the large run size and low temperature scenario.

Proportion of Return					
Arrival Timing	**Harvest Timing**	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Early	Early	Lower-River	0.04	0.44	0.52
	Centered	Lower-River	0.06	0.43	0.51
	Late	Lower-River	0.07	0.42	0.50
	NA	Terminal	0.10	0.38	0.52
	NA	No Harvest	0.13	0.87	0.0
Average	Early	Lower-River	0.04	0.45	0.51
	Centered	Lower-River	0.06	0.44	0.51
	Late	Lower-River	0.07	0.42	0.51
	NA	Terminal	0.10	0.38	0.52
	NA	No Harvest	0.13	0.87	0.0
Late	Early	Lower-River	0.03	0.46	0.51
	Centered	Lower-River	0.03	0.46	0.51
	Late	Lower-River	0.05	0.43	0.52
	NA	Terminal	0.08	0.39	0.52
	NA	No Harvest	0.10	0.9	0.0

Table A.2. Early, average and late arrival timing morality, escapement, and catch proportions for the large run size and high temperature scenario.

Proportion of Return					
Arrival Timing	Harvest Timing	Harvest Location	Mortality	Escapement	Catch
Early	Early	Lower-River	0.46	0.04	0.51
	Centered	Lower-River	0.45	0.04	0.51
	Late	Lower-River	0.53	0.01	0.46
	NA	Terminal	0.95	0.00	0.05
	NA	No Harvest	0.96	0.04	0.0
Average	Early	Lower-River	0.34	0.14	0.52
	Centered	Lower-River	0.35	0.12	0.52
	Late	Lower-River	0.47	0.03	0.50
	NA	Terminal	0.84	0.00	0.15
	NA	No Harvest	0.86	0.14	0.0
Late	Early	Lower-River	0.27	0.22	0.51

	Centered	Lower-River	0.30	0.19	0.51
	Late	Lower-River	0.36	0.13	0.52
	NA	Terminal	0.63	0.12	0.24
	NA	No Harvest	0.66	0.34	0.0

Table A.3. Early, average and late arrival timing morality, escapement, and catch proportions for the small run size and low temperature scenario.

Proportion of Return					
Arrival Timing	**Harvest Timing**	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Early	Early	Lower-River	0.10	0.79	0.11
	Centered	Lower-River	0.11	0.77	0.12
	Late	Lower-River	0.11	0.76	0.13
	NA	Terminal	0.12	0.77	0.11
	NA	No Harvest	0.13	0.88	0.0
Average	Early	Lower-River	0.10	0.79	0.11
	Centered	Lower-River	0.11	0.77	0.12
	Late	Lower-River	0.12	0.76	0.12
	NA	Terminal	0.12	0.77	0.11
	NA	No Harvest	0.12	0.88	0.0
Late	Early	Lower-River	0.08	0.81	0.11
	Centered	Lower-River	0.08	0.82	0.10
	Late	Lower-River	0.09	0.80	0.11
	NA	Terminal	0.10	0.79	0.11
	NA	No Harvest	0.07	0.93	0.0

Table A.4. Early, average and late arrival timing morality, escapement, and catch proportions for the small run size and high temperature scenario.

Proportion of Return					
Arrival Timing	**Harvest Timing**	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Early	Early	Lower-River	0.85	0.04	0.11
	Centered	Lower-River	0.86	0.04	0.10
	Late	Lower-River	0.85	0.04	0.11
	NA	Terminal	0.95	0.01	0.05
	NA	No Harvest	0.94	0.06	0.0
Average	Early	Lower-River	0.76	0.14	0.10

	Centered	Lower-River	0.75	0.14	0.11
	Late	Lower-River	0.73	0.15	0.12
	NA	Terminal	0.86	0.10	0.05
	NA	No Harvest	0.75	0.25	0.0
Late	Early	Lower-River	0.54	0.35	0.11
	Centered	Lower-River	0.53	0.35	0.12
	Late	Lower-River	0.60	0.29	0.11
	NA	Terminal	0.65	0.29	0.06
	NA	No Harvest	0.38	0.62	0.04

Table A.5. 40% and 74% Chilko mortality, escapement, and catch for the large run size, low temperature scenario.

Proportion of Return				
Stock Composition	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Chilko 74%	Lower-River	0.05	0.43	0.53
	Terminal	0.09	0.39	0.52
Chilko 40%	Lower-River	0.06	0.44	0.51
	Terminal	0.10	0.38	0.52

Table A.6. 40% and 74% Chilko mortality, escapement, and catch for the large run size, high temperature scenario.

Proportion of Return				
Stock Composition	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Chilko 74%	0.27	0.21	0.52	0.27
	0.72	0.00	0.28	0.72
Chilko 40%	0.35	0.12	0.52	0.35
	0.84	0.00	0.15	0.84

Small Run Size – Low Temperature

Table A.7. 40% and 74% Chilko mortality, escapement, and catch for the small run size, low temperature scenario.

Proportion of Return				
Stock Composition	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Chilko 74%	Lower-River	0.10	0.79	0.12

	Terminal	0.11	0.78	0.11
Chilko 40%	Lower-River	0.11	0.77	0.12
	Terminal	0.12	0.77	0.11

Small Run Size – High Temperature

Table A.8. 40% and 74% Chilko mortality, escapement, and catch for the small run size, high temperature scenario.

Proportion of Return				
Stock Composition	**Harvest Location**	**Mortality**	**Escapement**	**Catch**
Chilko 74%	Lower-River	0.66	0.23	0.11
	Terminal	0.74	0.18	0.08
Chilko 40%	Lower-River	0.75	0.14	0.11
	Terminal	0.86	0.10	0.05

Appendix B. Example Decision Tree for Selecting an Optimal Harvest Strategy

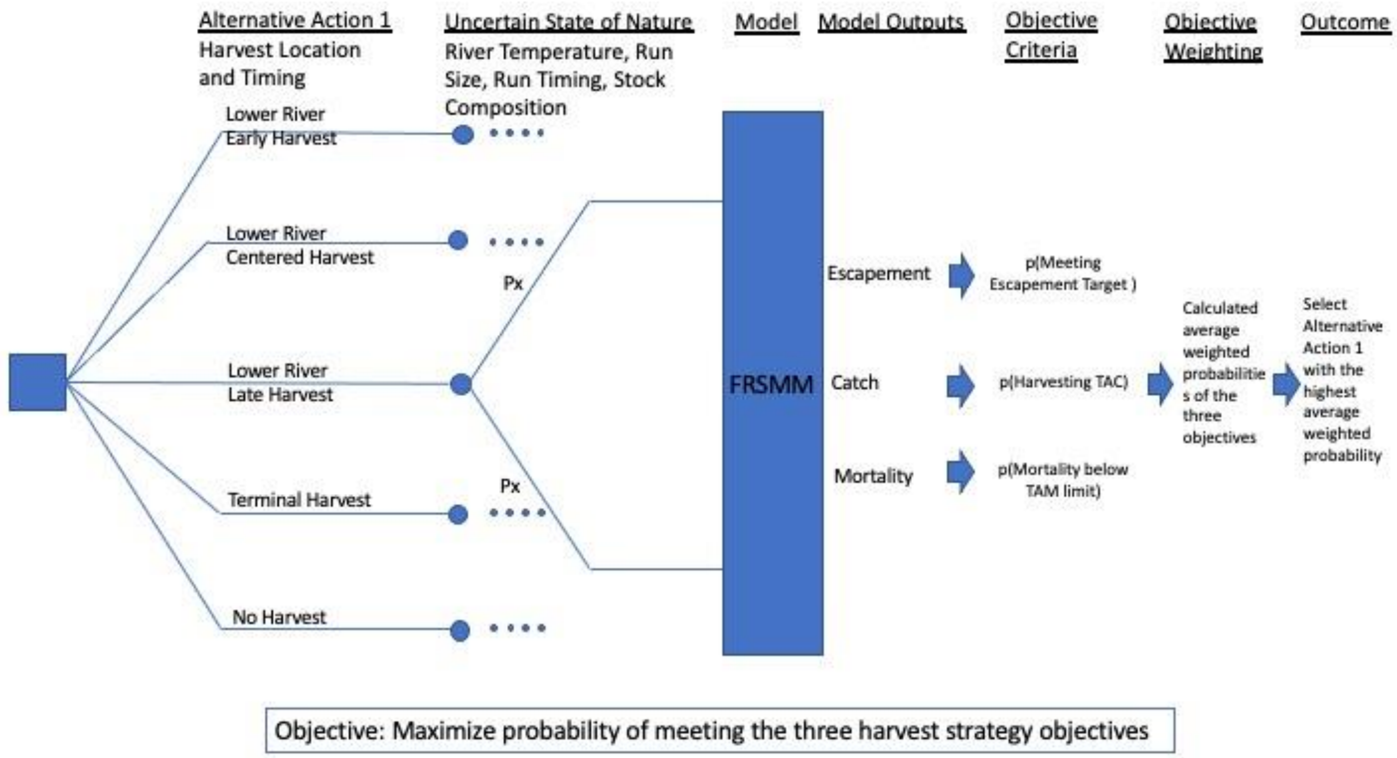

Figure B.1. **Example decision tree for selecting a optimal harvest strategy. Alternative actions are the harvest strategies available to the managers of the fishery, uncertain states of nature are the variable the managers cannot control (i.e. river temperature). Model outputs could be assessed by calculating the probability of meeting the fishery objectives.**